MASTER'S THESIS

Thermal Strategy

CLUSTER Long Eclipse Season 2012

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Master of Science (120 credits)
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Master Thesis

Msc in Space Technology

Thermal Strategy

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Acronyms

AOS	Acquisition Of Signal
ASPOC	Active Spacecraft Potential Control experiment
BTR	Batteries
CC	Central Cylinder
CIS	CLUSTER Ion Spectrometry
CODIF	Ion Composition and Distribution Function analyser
CTU	Central Terminal Unit
DWP	Digital Wave Processing
EDI	Electron Drift Instrument
EPD	External Power Dumper
FCT	Flight Control Team
FGM	Fluxgate Magnetometer
HIA	Hot Ion Analyser
HPA	High Power Amplifier
HPM	High Power Mode
HTR	Heater
IPD	Internal Power Dumper
LCL	Latching Current Limiter
LPM	Low Power Mode
MEP	Main Equipment Platform
MEOR	Mission Extension Operations Review
PEACE	Plasma Electron And Current Experiment (PEACE)
P/L	Payload
RCS	Reaction Control Subsystem
RTU	Remote Terminal Unit
SAP	Solar Array Power
SRL	Subsystem Reconnection Logic
STAFF	Spatio-Temporal Analysis of Field Fluctuation experiment
TCS	Thermal Control Subsystem
TTC	Telemetry Tracking and Command
TX	Transponder
WBD	Wide Band Data
WEC	Wave Experiment Consortium

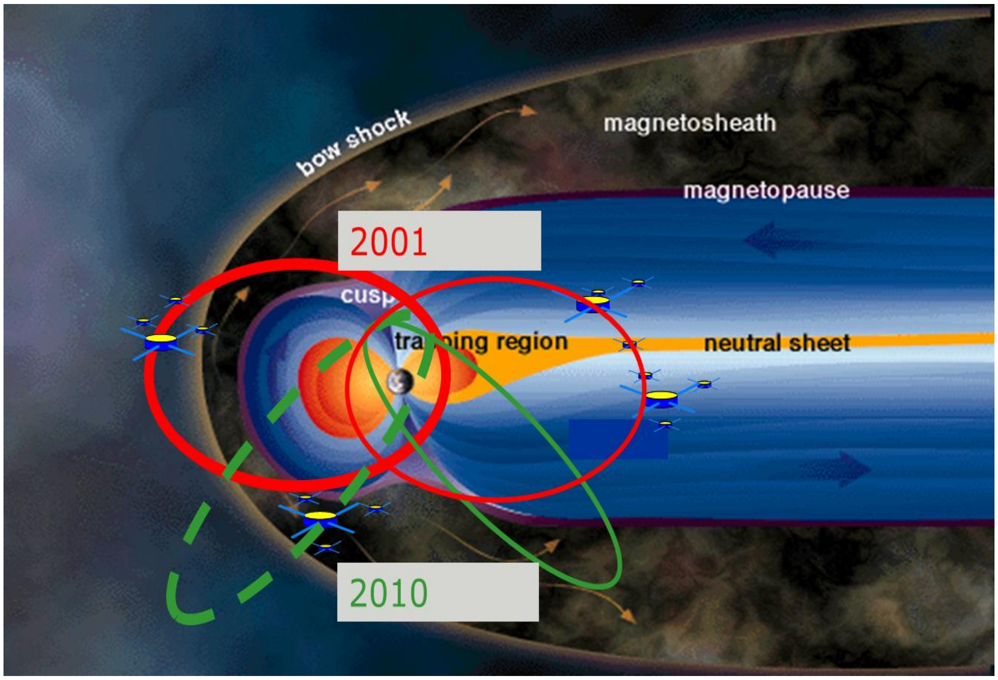
1. Introduction

1.1 Mission Definition

CLUSTER's mission concept has been proposed for the first time in 1982 and finally launched in 2000 by a Soyuz rocket from Baikonur Cosmodrome in Kazakistan in two pairs (spacecraft 1 and 4, and spacecraft 2 and 3). The mission is an international cooperation that, using four nearly identical spacecraft flying in formation, investigate the interaction between the solar wind and the Earth's magnetosphere in three dimensions.

The four spacecraft together collect data on small-scale changes close to Earth and the interactions between the charged particles of the solar wind and the magnetosphere of our planet. Data are used for studying three-dimensional and time-varying phenomena: scientists are able to build a three-dimensional model of the magnetosphere and study the process that occurs at this level. A result of the interaction previously described is for example the polar aurora.

In order to determine accurately these phenomena, CLUSTER needs four identical spacecraft which fly in non-coplanar highly eccentrically polar orbit at an altitude between 19000 and 119000 km crossing different regions (e.g. cusp, magnetopause, neutral sheet) [5].



1.2 Spacecraft structure

CLUSTER represents the first ESA mission where satellites have been produced in series: in order to fulfil the requirements four nearly identical satellites have been built. The four spacecraft present very small differences: for example SC2 and SC4 show an adapter ring –used for allocating two spacecraft per launch- which increases the irradiative surface (consequently SC2 and SC4 are colder than SC1 and SC3).

The satellites (**Figure 2**) are cylindrical with 2.9 m in diameter and 1.3m high. The dimensions have been kept to a minimum in order to fit the satellites inside the rocket during the launch.

1.2.1 Central Cylinder (CC)

The central part of the satellite consists of a cylinder made in aluminium honeycomb reinforced with a skin of carbon-fibre. This structure is used also for allocating units such as the five batteries and together with an inner platform it supports the units of the propulsion system (e.g. the helium tanks, the main engine).

1.2.2 Main Equipment Platform (MEP)

The Main Equipment Platform, directly attached to the central cylinder, is a panel in aluminium-skinned honeycomb. On it several units are mounted: the payload is mounted on the upper surface and other subsystems on the lower surface. The MEP temperature will play an important role in the development of this thesis work, because its temperature is the reference one used for measuring all the temperatures of the other units, provided a certain delta.

1.2.3 Solar Arrays (SA)

The Solar Arrays are attached to the Main Equipment Platform. Each satellite has six curved panels, in the outer cylinder.

1.2.4 Reaction Control Subsystem (RCS) support ring

Many of the Reaction Control Subsystem (RCS) units are accommodated at the end of the solar array panels, included also the two axial thrusters (10N per each). Remember that the position of the thrusters, and as such also the position of each unit mounted on board the satellite, is chosen in order to avoid contamination and interference for the objective of the mission.

1.2.5 Batteries (BTR)

Each spacecraft carries five Silver-Cadmium batteries on board.

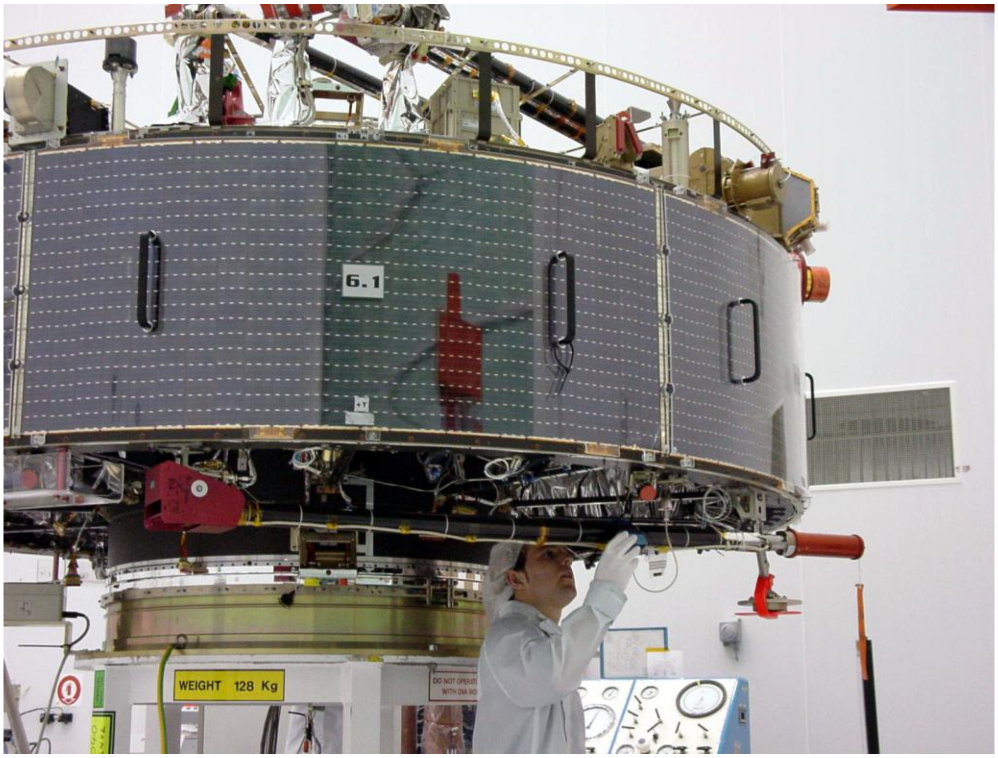


Figure 1: CLUSTER satellite construction at EADS Astrium, Bremen

1.2.6 External Power Dumper (EPD)

The external power dumpers are resistors attached to the central cylinder. They are used for dissipating the excessive power in the outer space. On board the satellite there are five EPDs with different dissipation capacity (an important role plays the EPD 80 W, as it will be explained later).

1.2.7 Internal Power Dumper (IPD)

The internal dumpers, instead, dissipate the power internally in the spacecraft and are also used to warm up the latter, playing an important role for the thermal control. Each satellite has sixteen IPDs that are equally spread on the MEP. Each IPD is able to dissipate 30W, for a total of 320 W.

1.2.8 High Power Amplifier (HPA)

Each spacecraft carries two High Power Amplifier (one main and one redundant). This unit is used for amplifying the transmitter signal before it is sent to the antenna. Due to the high dissipation, the HPAs are mounted on a dedicated radiator and a special heater (HTR E) is used for keeping it warm. This unit can be operated in High Power Mode (HPM) or Low Power Mode (LPM) or can be kept OFF (such as it happens during the Long Eclipse Season 2012).

1.2.9 Antennas

On board the satellites there are two antennas, both low gain (broad radio wave beam width). The two antennas are mounted in the opposite sides of the satellites (upper face and lower face), and depending on the position of the satellite in the orbit, one of the two is selected from ground in order to establish the communication with the antenna on Earth. For the uplink, they ensure the full spherical coverage, while for the downlink they ensure hemispherical coverage. Before the deployment of the lower antenna boom, a third antenna is used, which is mounted on the RCS-Ring.

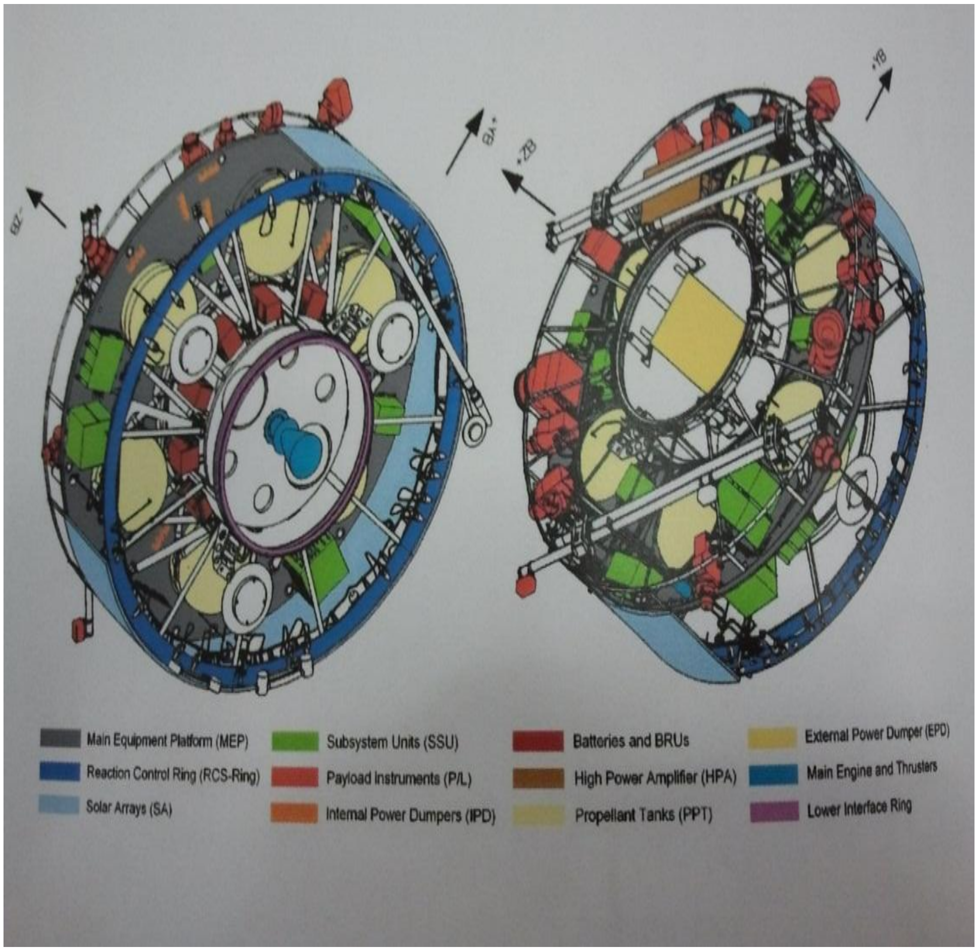


Figure 2: CLUSTER design

1.3 Payload (P/L)

The four satellites carry eleven scientific instruments which study electric and magnetic fields and waves. The instruments are the same on board each spacecraft, which allows the collection of detailed information regarding the phenomena in the different regions of the Earth magnetosphere. Five of the instruments are grouped in the Wave Experiment Consortium (WEC).

1.3.1 Plasma Electron And Current Experiment (PEACE)

This instrument is used for analysing the composition, mass and distribution functions of ions in the space plasma and in the solar wind during each four second spin of the spacecraft. It consists of two sensors (see **Figure 3**: The two sensors of the instrument PEACE) that are placed on the opposite side of the satellite: the Low Energy Electron Analyser (LEEA), and the High Energy Electron Analyser (HEEA). The HEEA is used for the higher end of the range of energy, while the LEEA is used for the lower energy ranges. The instrument also presents the Data Processing Unit (DPU).

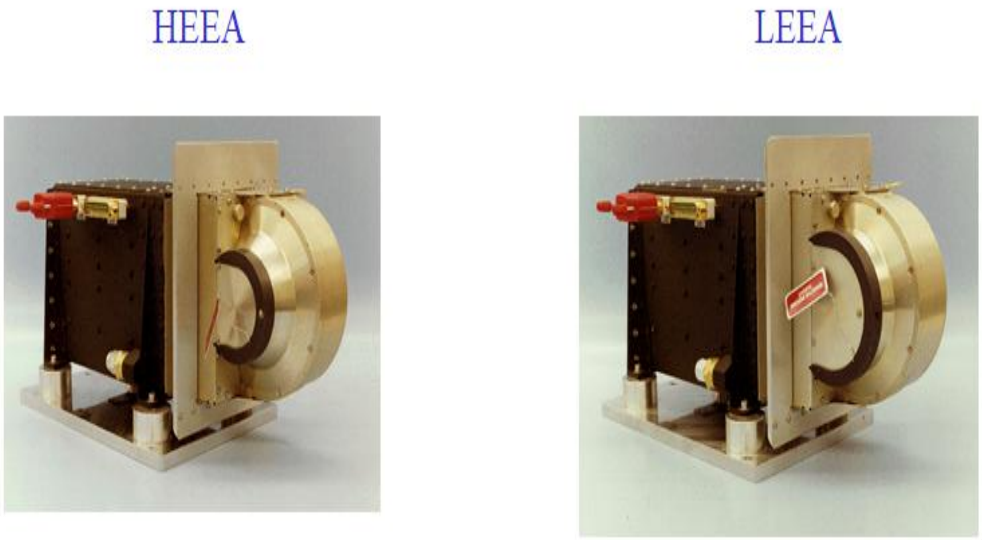


Figure 3: The two sensors of the instrument PEACE

1.3.2 Electric Field and Wave experiment (EFW)

This instrument is used to measure the electric field for the study of plasma convection and waves. It uses sensors placed on four wire booms that extends for 50 m. The capacity of this instrument is quite high: it is able to collect up to 36000 samples per second of the electric field and fluctuations of the density of plasma. In this way also waves that travels at a speed of thousand kilometres per second can be detected.

1.3.3 Wide Band Data Instrument (WBD)

This instrument detect electric and magnetic fields in selected wavelength with very high resolution. In particular it is able to detect radio whistles and hisses from particles trapped in a bounce motion in the poles.

1.3.4 Fluxgate Magnetometer (FGM)

On board each satellite there are two magnetometers that study the magnetic field along the orbit. With a lower capacity compared to the EFW, this instrument is able to collect up to 67 samples per second. In order to not be disturbed by the spacecraft's interferences, the magnetometers are located on a five meter long boom that extends form the spacecraft main body.

1.3.5 Spatio-Temporal Analysis of Field Fluctuation experiment (STAFF)

This instrument consists of a magnetometer placed in a five meter long boom. It studies the variations in the magnetic field, particularly in those regions where the interaction between charged particle from solar wind and the Earth's magnetosphere occurs. Regarding the data collected, two different processing are applied: the one at low frequency is done on ground, while the one at high frequency is done directly on board.

1.3.6 Digital Wave Processing experiment (DWP)

This instrument is used for the control and use of the power and telemetry-information for the instrument grouped in the WEC. It is also used for the time correlation between the four spacecraft. Moreover it enables the variation in the electron population around the satellite to be compared with the measurements of the waves.

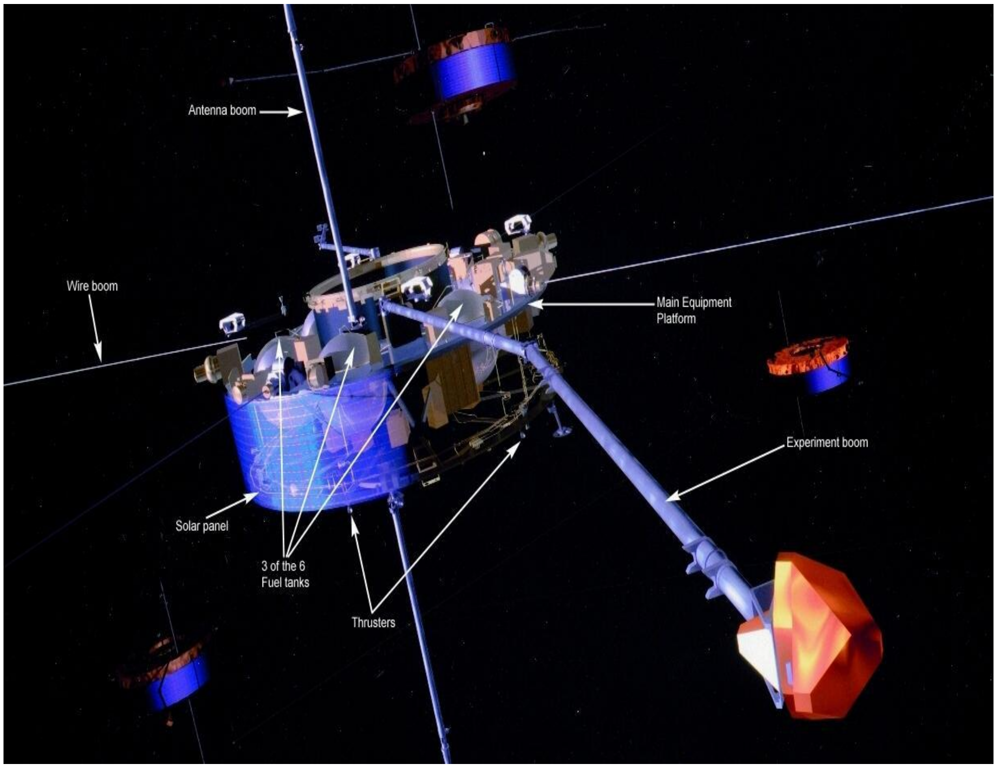


Figure 4: CLUSTER satellite with extended experiment booms.

1.3.7 Active Spacecraft Potential Control experiment (ASPOC)

By emitting ions (whose current is adjusted using other instruments on board), the goal of this instrument is to cancel the effects of spacecraft charging.

1.3.8 Waves of High frequency and Sounder for Probing of Electron Density by Relaxation experiment (WHISPER)

This instrument is used for several goals. First of all it is used for studying wave generation and energy transfer caused by charged particles. Moreover it studies the activity of the waves in a selected frequency range (2 to 80 kHz). In order to make the studies, this instrument uses the radar technique (short pulses are sent and then the instrument waits for the echo).

1.3.9 CLUSTER Ion Spectrometry experiment (CIS)

This instrument is used for measuring the energy and velocity of particles (i.e. ions) in order to identify them and try to understand from where they are from. Passing through a pinhole, the particles reach a detector. The highest energy electrons and ions are recorded once they enter the instrument.

1.3.10 Electron Drift Instrument (EDI)

The Electron Drift Instrument (EDI) is used in order to determine the strength of the electric and magnetic fields. In order to do it, electrons beams are artificially injected and their drift velocity is measured. The electrons are fired 10 km or more into the space around the spacecraft and eventually they return on the opposite side of the satellite itself. The instrument has two Gun Detector Units (GDUs) and a Controller Unit (see **Figure 5**).

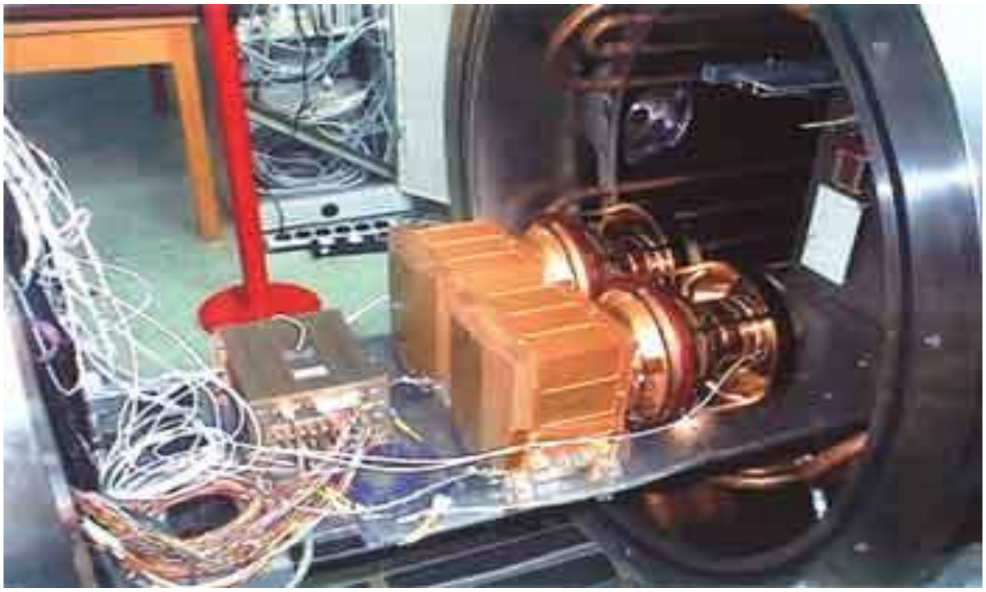
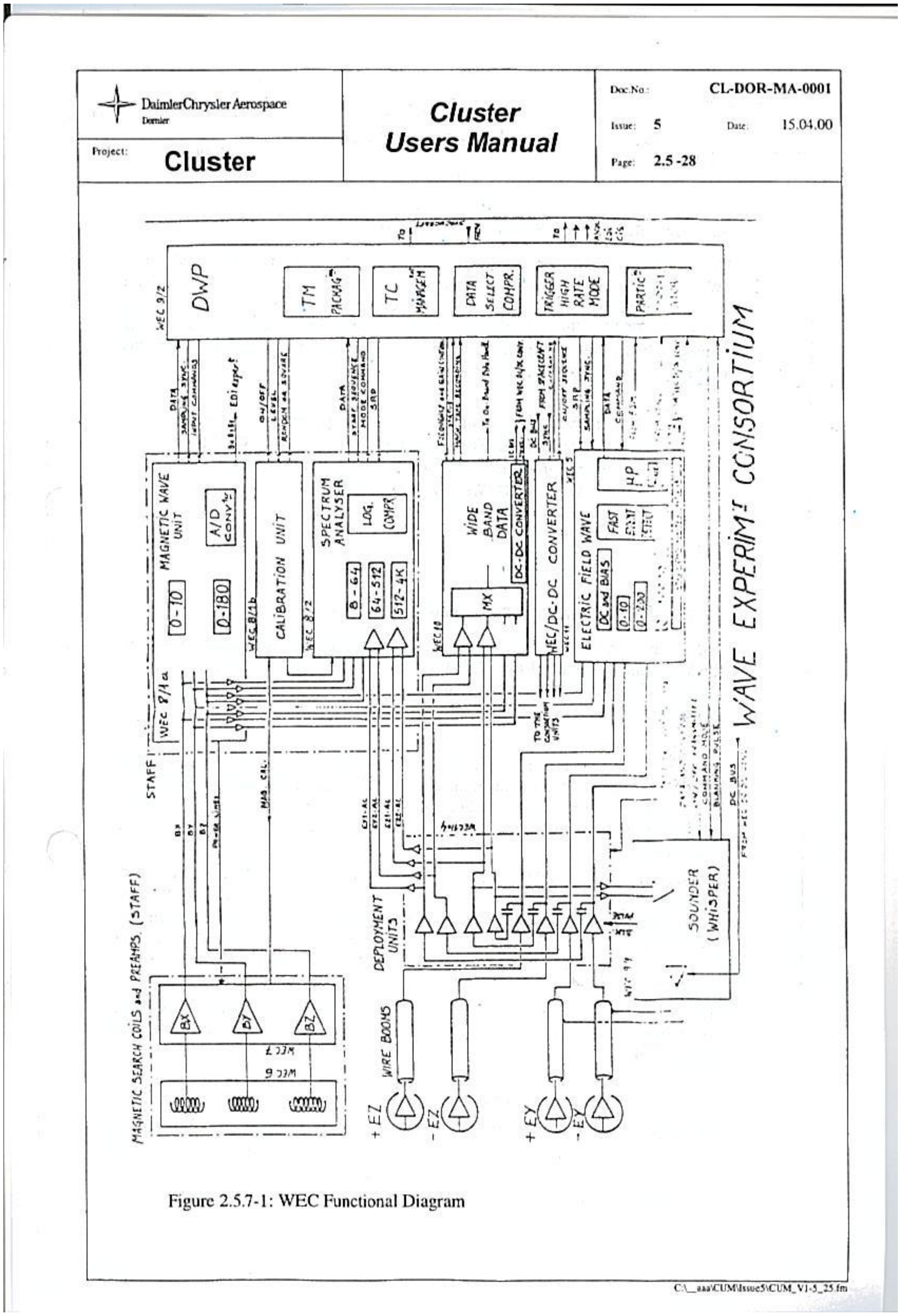


Figure 5: EDI being tested before the installation on board the satellite

1.3.11 Wave Experiment Consortium (WEC)

The Wave Experiment consortium groups five of the instrument that are carried on board the four CLUSTERs (i.e. STAFF, EFW, DWP, WHISPER, WBD). The functional diagram of the WEC can be seen in **Figure 6.** The aim of this consortium is to study the turbulences of plasma (in particular studying the critical layers) and also other parameters of the latter, such as the total density, the electric field, the variations in the domains of time and space and the parameters linked to these variations.


DaimlerChrysler Aerospace
Dornier

Project: **Cluster**

Cluster Users Manual

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Figure 2.5.7-1: WEC Functional Diagram

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Figure 6: Wave Experiment Consortium diagram

2. Long Eclipse Season 2012

2.1 The eclipse

An eclipse is the partial or total occultation of a body from the shadow of another one. During the event, the occulted body will experience a first period of penumbra followed by the umbra and then again penumbra before the total illumination. During penumbra, light is partially blocked, while during the umbra the body is totally shadowed.

2.2 CLUSTER Eclipses

In the case of CLUSTER, the four satellites are shadowed by the Earth (see **Figure 7**) and the Moon. A careful analysis shows that the four satellites experience two eclipse seasons per year: when close to the perigee the satellites face short eclipses, when close to apogee they face long eclipses. The first ones can last up to 43 minutes, while the second ones up to 214 minutes.

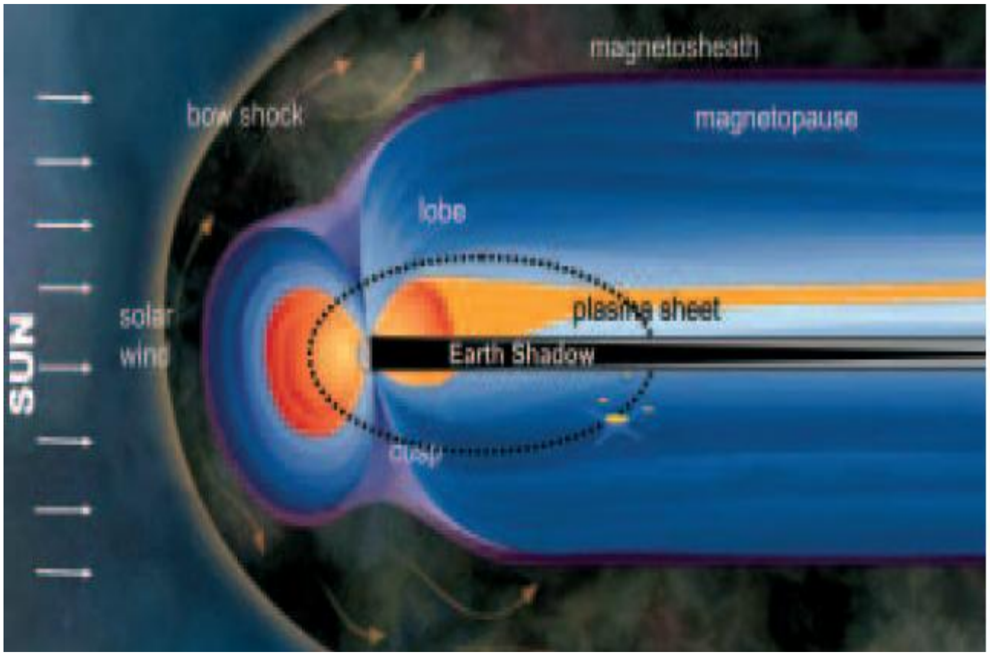


Figure 7: CLUSTER eclipses due to the Earth's shadow

Parameters such as the eclipse's length, the spacecraft power and thermal status, lead to the selection of different eclipse configuration. In order to define the optimised strategy from the energy and operation point of view, different types of eclipses are identified depending on the total time of occultation and available energy stored in the batteries (when applicable). As such we can define two big groups of eclipses under the names of *Normal Eclipses* and *Contingency Eclipses* [3].

The normal eclipses were the ones occurring at the beginning of the mission when the SAP was higher and batteries were available. Among them[4]:

- **Nominal Short Eclipses:** Full SC operations including Payload and HPA in LPM
- **Minimum Short Eclipse:** Full SC operations but Tx and HPA OFF
- **Power Limited Eclipse:** Heaters and payload operations limited to 90W consumption
- **Nominal Long Eclipses:** Reduced SC operations with Payload and HPA OFF (Flux Gate Magnetometer (FGM) in stand-by)
- **Minimum Long Eclipse:** Same as Nominal Long + Solid State Recorder (SSR) and FGM OFF.

Currently, due to the change in the satellites' characteristics, the contingency eclipses are the ones that the satellites experience, especially during the long eclipse seasons. Among them:

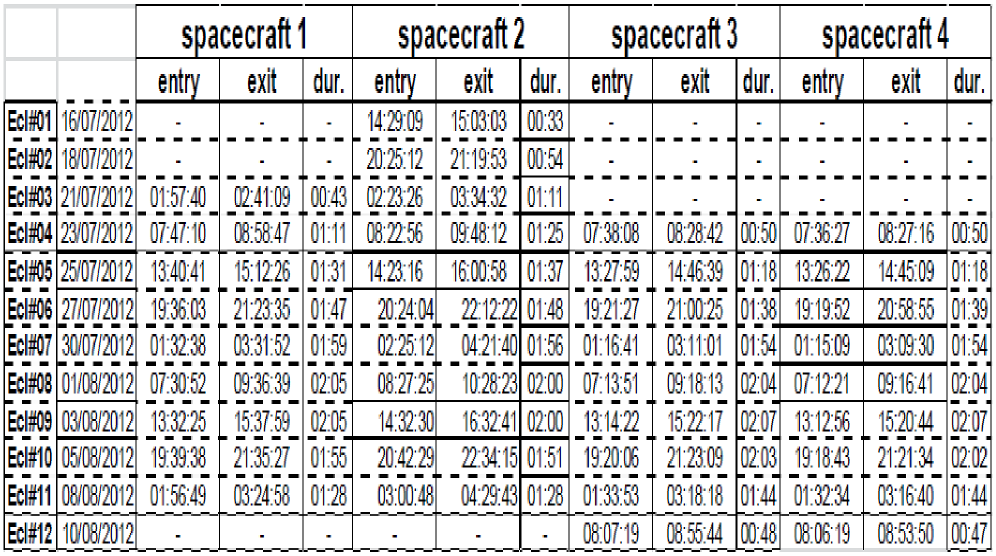
- **Decoder Only Eclipse:** All switchable loads OFF including Central Terminal Unit (CTU) and Remote Terminal Unit (RTU).
- **TT Power Down Eclipse without batteries:** the SC enters the eclipse as a Minimum Long configuration (TT), and batteries disabled when in umbra (Power Down).

- **NO Battery Eclipse:** the SC enters the eclipse in Decoder Only configuration (RT), and batteries disabled (Power Down)
- **TT No battery Power Down Eclipse:** the SC enters the eclipse with CTU OFF (TT) and RTU on. Batteries are disabled (Power Down).

Among them we focus on the NO BATTERY mode, that is the one applied to the long eclipse season 2012.

2.3 Eclipse season 2012 overview

The long eclipse season 2012 starts the 16th of July (SC 2) and finishes the 10th of August (SC3 and SC4). The eclipses' length will increase up to two hours and seven minutes (**Figure 8**).



		spacecraft 1			spacecraft 2			spacecraft 3			spacecraft 4		
		entry	exit	dur.	entry	exit	dur.	entry	exit	dur.	entry	exit	dur.
Ecl#01	16/07/2012	-	-	-	14:29:09	15:03:03	00:33	-	-	-	-	-	-
Ecl#02	18/07/2012	-	-	-	20:25:12	21:19:53	00:54	-	-	-	-	-	-
Ecl#03	21/07/2012	01:57:40	02:41:09	00:43	02:23:26	03:34:32	01:11	-	-	-	-	-	-
Ecl#04	23/07/2012	07:47:10	08:58:47	01:11	08:22:56	09:48:12	01:25	07:38:08	08:28:42	00:50	07:36:27	08:27:16	00:50
Ecl#05	25/07/2012	13:40:41	15:12:26	01:31	14:23:16	16:00:58	01:37	13:27:59	14:46:39	01:18	13:26:22	14:45:09	01:18
Ecl#06	27/07/2012	19:36:03	21:23:35	01:47	20:24:04	22:12:22	01:48	19:21:27	21:00:25	01:38	19:19:52	20:58:55	01:39
Ecl#07	30/07/2012	01:32:38	03:31:52	01:59	02:25:12	04:21:40	01:56	01:16:41	03:11:01	01:54	01:15:09	03:09:30	01:54
Ecl#08	01/08/2012	07:30:52	09:36:39	02:05	08:27:25	10:28:23	02:00	07:13:51	09:18:13	02:04	07:12:21	09:16:41	02:04
Ecl#09	03/08/2012	13:32:25	15:37:59	02:05	14:32:30	16:32:41	02:00	13:14:22	15:22:17	02:07	13:12:56	15:20:44	02:07
Ecl#10	05/08/2012	19:39:38	21:35:27	01:55	20:42:29	22:34:15	01:51	19:20:06	21:23:09	02:03	19:18:43	21:21:34	02:02
Ecl#11	08/08/2012	01:56:49	03:24:58	01:28	03:00:48	04:29:43	01:28	01:33:53	03:18:18	01:44	01:32:34	03:16:40	01:44
Ecl#12	10/08/2012	-	-	-	-	-	-	08:07:19	08:55:44	00:48	08:06:19	08:53:50	00:47

Figure 8: CLUSTER Long eclipse season 2012 times

The Solar Array Power is considerably decreased compared to the beginning of the mission. **Figure 9** shows the evolution of the SAP: in July 2000, the power is around 280 W, while in July 2012 it is on average around 180W (obviously this is different for each spacecraft as can be seen in the picture). Moreover it is really difficult to make predictions, which gives more uncertainty on the strategy definition.

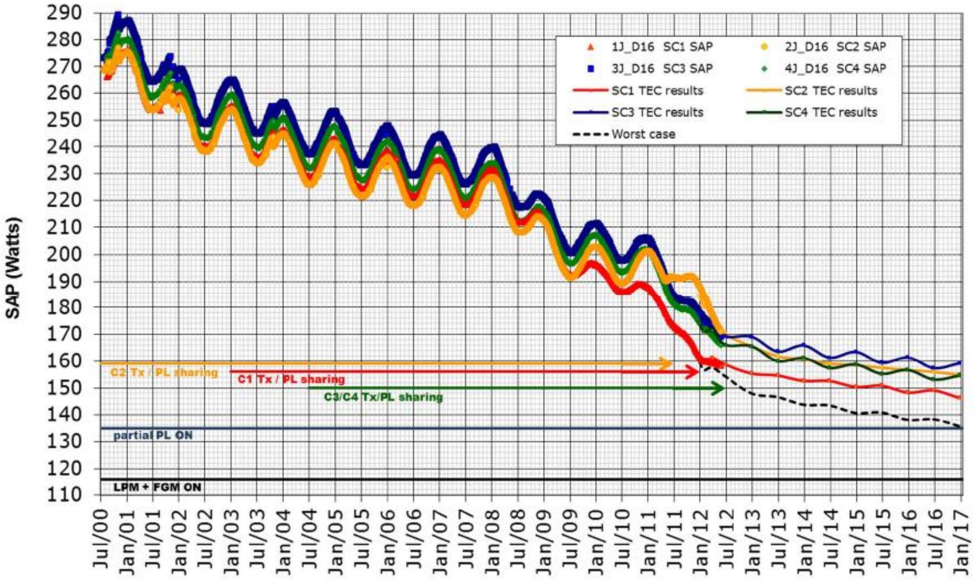


Figure 9: Solar Array Power evolution

Regarding the battery status, SC1 has no operational battery left, SC3 and SC4 have only one battery available (which ,nevertheless, is too weak to be used during the long eclipse season 2012), SC2 has still three batteries available and these will be used for the first eclipse of the season (shorter compared to the other ones), while all the other eclipses will be NO BATTERY.

Currently, during routine operations, the equilibrium MEP temperature is much lower compared to the last long eclipse season (in 2009). The temperature of SC 1 and SC3 is a bit higher (~ 10°C) compared to the one of SC2 and SC4 (SC2 is ~ 7°C and SC4 is ~6°C).

In order to avoid problems such as the freezing of the oxidizer in the pipes, the MEP temperature at the eclipse's exit should be kept possibly above 0°C. Moreover the High Power Amplifier (HPA) temperature should be carefully monitored.

2.4 Eclipse operations

During eclipses no sun radiation heats the satellites, and also no solar array power is available. This results in a faster cooling down of the satellite's units and triggering of heating elements which increase the power consumption.

The first step is to switch off all the non-essential loads: i.e. the scientific instruments (no science operations are run during eclipse phase), HPA, and transmitter (no data are received from the satellite until Solar Array Power (SAP) will be enough to switch on the Telemetry Tracking and Command (TTC) subsystem).

Normally, when SAP is not available, the energy is taken from the batteries. Nevertheless, as already mentioned, the latter cannot be used for the long eclipses of 2012.

All these factors lead to what is called a NO BATTERY Eclipse: complete power down with empty batteries. The operations of pre-eclipse are done in real time, and the Central Terminal Unit (CTU) (central unit for the primary spacecraft control functions) is OFF until the next ground contact. The post- eclipse operations are also done in real time.

Starting from the 16th of July the four satellites face the critical phase of the long eclipse season 2012. As it will be shown, CLUSTER 1 and 3 are warmer than CLUSTER 2 and 4 after eclipse for both MEP and HPA temperatures. Under the conditions previously described, this is a risky, challenging and interesting phase of the mission.

3. Purpose of the Master Thesis

Due to the successful collected results, the mission, firstly planned to last only two years, has been extended several times, first up to 2005, then 2009, 2014 and currently an extension up to 2016 has been requested. Sun and Moon influence leaded to a change in the orbit of the spacecraft. The orbital period was also decreased from 57 to 54 hours due to an apogee lowering (~5000km).

Despite the fact that new results are achieved, the conditions of the satellites are worsening during time. The solar arrays have deteriorated and also the batteries cannot be used anymore. One more factor that should be taken into account is that due to their orbit, the four spacecraft experience eclipse season each winter and each summer. Especially during these critical periods, a special monitoring of the satellite is conducted and a thermal and power strategy has to be defined. Some critical units have to be carefully monitored, such as HPA and RCS pipes, whose temperature risks to be under the threshold limit (see below).

Based on a model [2] previously created for the long eclipse season of 2006, a new thermal strategy has to be developed. Due to its characteristics (specific only for September 2006), the model was not totally reliable and thus a few changes have been introduced such that the model became reliable for any period of the year and for any year. The telemetry from January 2009 to June 2012 has been analysed in order to study the trend behaviour, and in particular specific cases for understanding the differences occurring when different configuration were affecting the spacecraft. The study, the improvements in the model, the spacecraft condition and the new requirements have been used for developing the new strategy. In particular the study of an anomaly that occurred in 2011 has been carried out giving the possibility of explaining the event and also, with the understanding of specific factors, the results have been used in the new thermal strategy.

4. Thermal Control

During the different phases of the mission the thermal requirements varied significantly. First of all different conditions occur depending on the position of the satellite in the orbit itself: for example, when at perigee, the albedo flux gives a strong contribution, and also the planetary radiation itself. Moreover different events can occur and they significantly influence the thermal conditions: for example during eclipses no sun radiation heats the satellite which, consequently, will suffer for the lack of power.

The goal of the Thermal Control System is to maintain the temperatures of the units within their acceptable ranges. The thermal control is normally done in two ways: passive control (e.g. by using specific surface properties) and active control (e.g. heat pipes and thermostat).

4.1 Thermal Control Subsystems

Regarding CLUSTER it is possible to individuate four nearly independent groups of the Spacecraft Thermal Control:

- HPA, with its dedicated radiator for the heat rejection and a heater for maintaining the temperature within the operating temperature range, especially during critical phases such as the contingency eclipses.
- Thrusters and Main Engine, where each thruster has a dedicated heater mat from a specific circuit, and the main engine heater is powered from another dedicated circuit.
- Boom Mounted Experiments, Starmapper Apertures and Protruding Experiment, characterized by a passive thermal control.
- Spacecraft Internal Units, whose temperature is related to the MEP one.

As mentioned before, the most important temperature value that needs to me monitored is the MEP temperature, because starting from it, it is possible to calculate the temperatures of all the other units of the spacecraft, provided a certain delta. Ideally the MEP temperature should be kept above 0 °C, also during critical phases (e.g. eclipses). The average MEP temperature’s time constant is about 12 hours and it describes the internal environment.

The critical periods for the CLUSTER satellites are the eclipse seasons, and in particular the long eclipse ones. Especially these events are becoming every time more critical due to the worsening of the conditions of the spacecraft subsystem units. As a matter of fact, no storage of power is possible (the batteries' capacity is such that they cannot be used during eclipses, and also the solar arrays' power is considerably decreased), thus the thermal control becomes a very difficult issue for the operations of the fours spacecraft. For example IPD Power is quite low and also more important is the fact that also during normal operations the four satellites are considerably much colder than at the beginning of the mission (especially CLUSTER 2 and 4).

Another important factor that should be taken into account is the solar flux. The solar radiation intensity is inversely proportional to the square of the distance. The solar constant is varying during one year between 1320W/m^2 and 1420 W/m^2. The variation of the latter according to the period of the year can be seen in the following **Figure 10.**

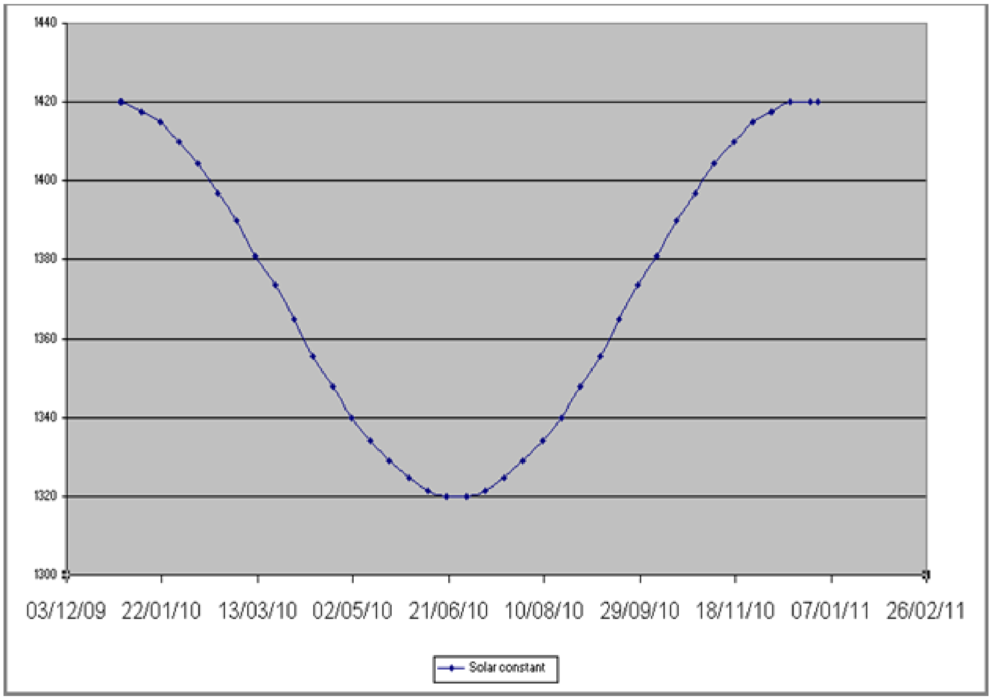


Figure 10: Solar Constant variation

5. Thermal Model of 2006

5.1 Requirements

The eclipses of September 2006 represent the first critical period where already the lack of enough power on board the satellite was clear. For this reason Markus Pietras developed as his master thesis a model that needed to be used for the predictions of the MEP temperature [2]. The model wanted to be fast and easy to be used, accurate for the predictions of all the four spacecraft and able to make long term predictions with different power settings. Several options have been considered at the beginning, included the ESATAN model, but they all resulted not enough accurate or too much detailed. The following assumptions are used for the model construction:

- Conduction is considered negligible and only radiation is taken into account
- The emissivity is constant over temperature and time
- Direct proportionality between the heat transfer from IPDs and subsystem units to the MEP , and their power consumption
- The heat flow depends on the solar constant only

5.2 ESA Thermal Analysis Network (ESATAN)

The ESATAN software has been released in 1985 and since then used by ESA as its standard thermal analysis code.

It is based on the definition of nodes , conductance and material properties, in order to obtain the required steady-state temperature.

The method used by the software is the lumped parameter approach and use a FORTRAN-like syntax for its code structure [7].

Nevertheless this software would require a detailed preparation for each simulation, it requires good knowledge from the user and also it is not verified the possibility of long-term analysis.

5.3 Single Node Approach

The temperature of the main equipment platform is a key parameter for the thermal conditions of the spacecraft: as a matter of fact the temperatures of the other units on board the satellite can be related to the MEP one and calculated according to a fixed delta. For this reason it has been chosen a model which works in a single node approach, where indeed the MEP temperature is the monitored value.

Many parameters that will be taken into account for the definition of the equation that will be used for the determination of the MEP temperature, are often unknown. In order to determine them the available telemetry from the past seasons has been used.

Some of the parameters that will be inserted in the equation are constant during the year, while some others depend on the seasonal change as a function of other parameters such as the solar constant that can be defined for every date.

By taking into account some factors such as the limitations in the heat flow given by the IPD power and other unit dissipation, and also the efficiency parameters, and so on, Markus Pietras derivated the MEP temperature according to the following:

$$C\frac{dT}{dt} = \alpha T^4 + \eta_{IPD} * \dot{Q}_{IPD} + \eta_{SSU} * \dot{Q}_{SSU} + \dot{Q}_S \qquad (3.2.1)$$

Where respectively each symbol is:

- C = MEP thermal capacitance
- $\frac{dT}{dt}$ = Temperature Gradient
- α = Stefan-Boltzmann constant
- T = MEP Temperature
- η_{IPD}= Efficiency of the heat transfer from the IPDs to the MEP
- $\dot{Q}_{IPD}$ = Heat flow from the IPDs to the MEP
- η_{SSU} = Efficiency of the heat transfer from the dissipating units to the MEP

- $\dot{Q}_{SSU}$ = Heat flow from the dissipating units to the MEP
- $\dot{Q}_{S}$ = Remaining solar heat flow to the MEP

5.4 User interface

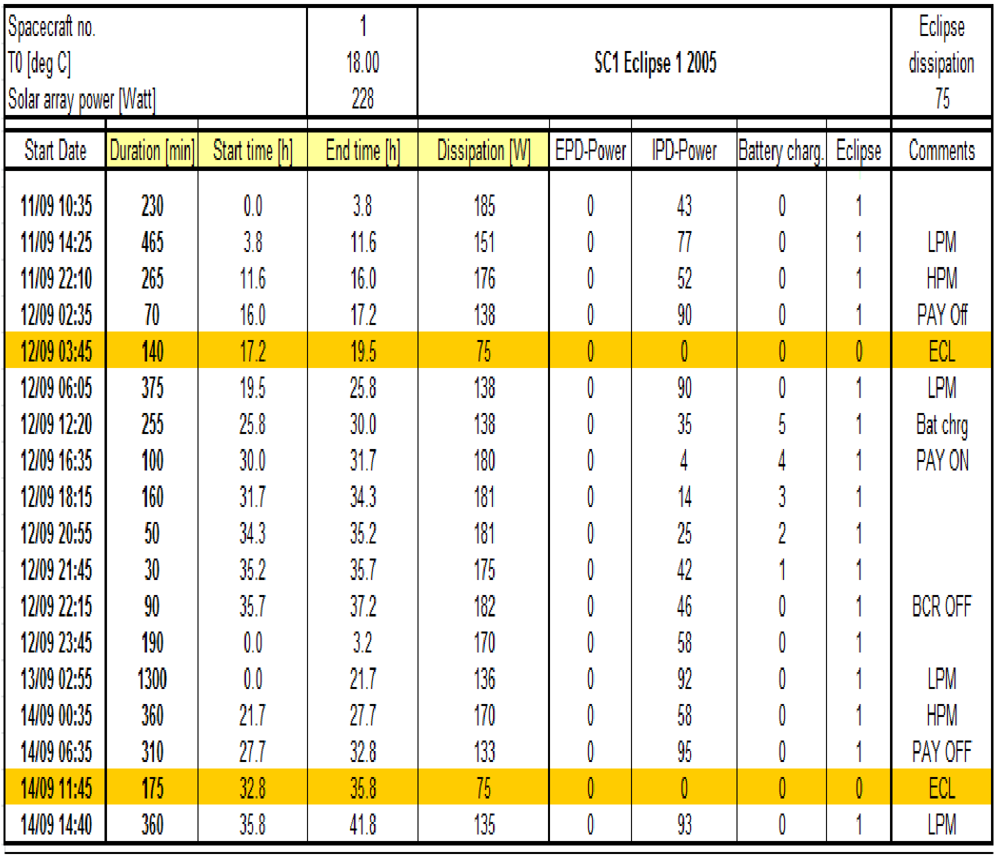
The model is developed with MS Excel and it allows eighteen sequent steps. Some parameters have to be inserted manually, while others are calculated depending on these inputs and other factors. In particular the needed input are the following:

- Start time
- Solar Array Power (SAP)
- EPD Power
- IPD Power
- Batteries charging
- Solar Constant
- Spacecraft Number
- Eclipse yes/no
- Dissipation during eclipse

Some other parameters can be individuated in the model, but are calculated in the background. In particular the dissipation is calculated as follow:

$$\dot{Q}_{dis} = SAP - P_{IPD} - P_{EPD} \qquad (3.3.1)$$

Where P_{IPD} and P_{EPD} are the power dissipated respectively in the IPDs and EPDs.



Spacecraft no. T0 [deg C] Solar array power [Watt]	1 18.00 228	SC1 Eclipse 1 2005	Eclipse dissipation 75

Start Date	Duration [min]	Start time [h]	End time [h]	Dissipation [W]	EPD-Power	IPD-Power	Battery charg.	Eclipse	Comments
11/09 10:35	230	0.0	3.8	185	0	43	0	1	
11/09 14:25	465	3.8	11.6	151	0	77	0	1	LPM
11/09 22:10	265	11.6	16.0	176	0	52	0	1	HPM
12/09 02:35	70	16.0	17.2	138	0	90	0	1	PAY Off
12/09 03:45	140	17.2	19.5	75	0	0	0	0	ECL
12/09 06:05	375	19.5	25.8	138	0	90	0	1	LPM
12/09 12:20	255	25.8	30.0	138	0	35	5	1	Bat chrg
12/09 16:35	100	30.0	31.7	180	0	4	4	1	PAY ON
12/09 18:15	160	31.7	34.3	181	0	14	3	1	
12/09 20:55	50	34.3	35.2	181	0	25	2	1	
12/09 21:45	30	35.2	35.7	175	0	42	1	1	
12/09 22:15	90	35.7	37.2	182	0	46	0	1	BCR OFF
12/09 23:45	190	0.0	3.2	170	0	58	0	1	
13/09 02:55	1300	0.0	21.7	136	0	92	0	1	LPM
14/09 00:35	360	21.7	27.7	170	0	58	0	1	HPM
14/09 06:35	310	27.7	32.8	133	0	95	0	1	PAY OFF
14/09 11:45	175	32.8	35.8	75	0	0	0	0	ECL
14/09 14:40	360	35.8	41.8	135	0	93	0	1	LPM

Figure 11: MEP tool Input table

Figure 11 shows a screenshot of the Input Table of the model. It is possible to identify the input parameters previously mentioned. The spacecraft considered is SC1, the available SAP is 228 W, and the starting temperature is set at 18°C. The covered period starts the 11-09-2005 at 10:35 until 14-09-2005 at 14:40. IPD Power is 43 W and no EPD Power. We can individuate how many batteries are charging and at which time. The yellow lines indicate when the eclipse occur (number 0 in the eclipse column indicates that the event is occurring). The dissipation during eclipse can be inserted on the top right (it is valid for each eclipse) or can be inserted manually in case of different values per each eclipse. The duration is calculated between two sequent steps and inserted at the level of the top one. The dissipation is calculated according to **Equation 3.3.1**, for example for the first row we have SAP = 228, P_{EPD} = 0, P_{IPD} = 43W, thus dissipation is 185 W. The output of the model is the MEP temperature. Note that the starting temperature (top left of the model) can be inserted manually.

In order to develop the model and adjust it where needed, the telemetry from the previous years was retrieved to get a trend of the data and compared to the output of the model in order to adjust it and be able to make further predictions.

The model gave very good predictions which were useful during the long eclipse season of September 2006. Nevertheless when applied to other months of 2006 and to other years, the model was not fully reliable as the predictions were deviating from the real telemetry (**Figure 12**).

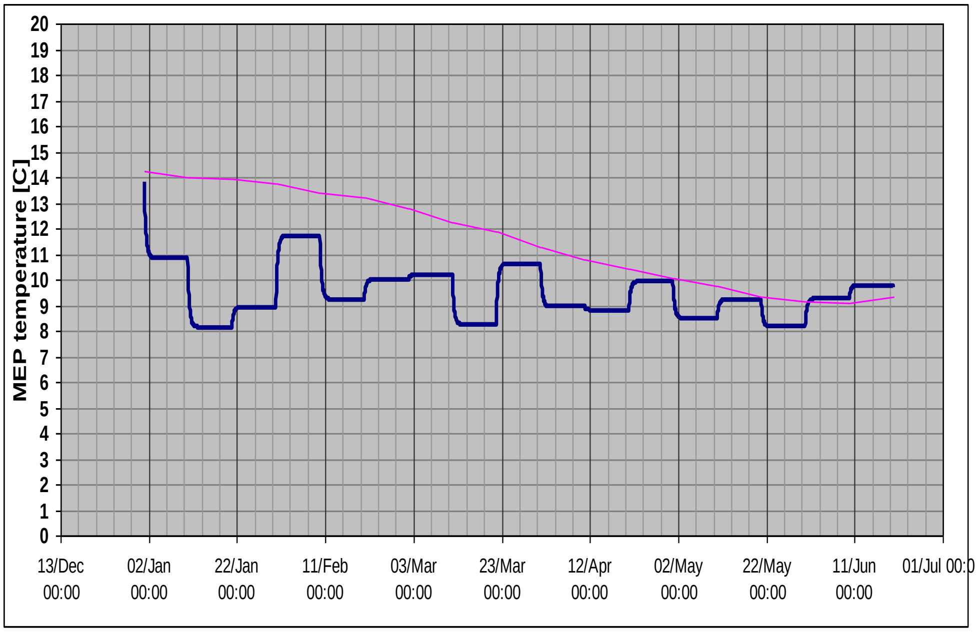


Figure 12: SC 3, Jan-Jun 2010 using the model developed by Markus Pietras. The blue line represents the model predictions, the pink line represents the telemetry

6. Model improvements

6.1 Analysis

The long eclipse season of July 2012 is the most critical after the model has been developed and when not reliable a few changes have to be introduced. **Figure 13** shows the eclipse seasons starting in 2009 up to 2012 (each colour represents one spacecraft). On the left axis the length can be read and on the right axis the date. The eclipses in 2009 were longer than the ones in 2012, but the spacecraft presented better conditions (i.e. better SAP and batteries available).

The most critical eclipses for the long eclipse season 2012 are the central ones where the length exceed 2 hours in duration. These eclipses are operated in NO BATTERY mode.

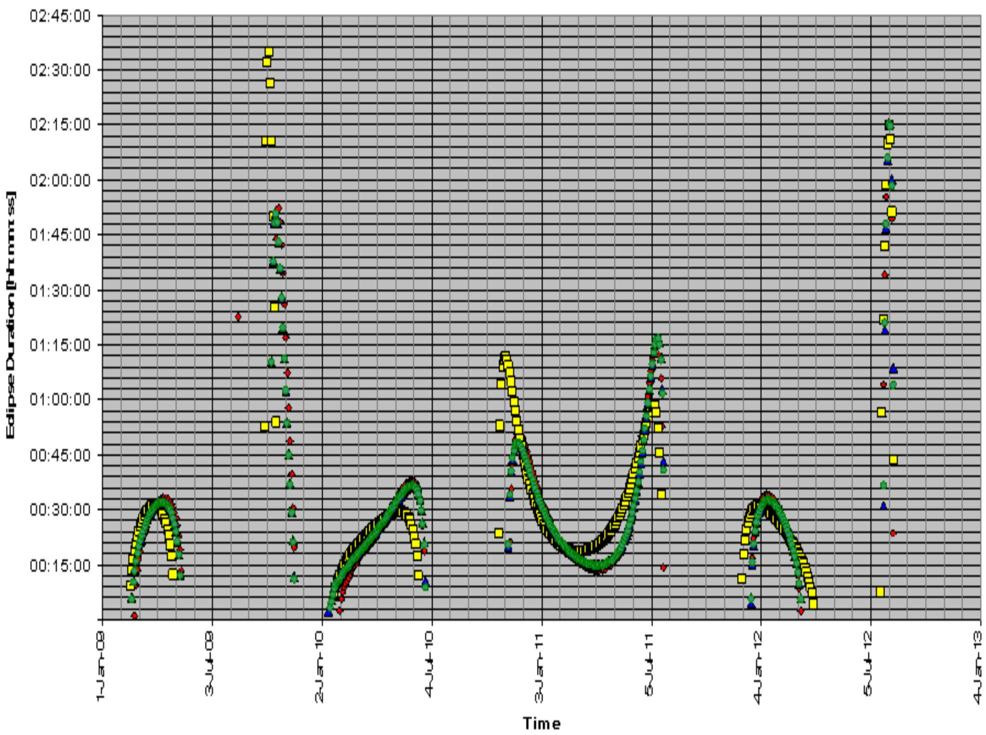


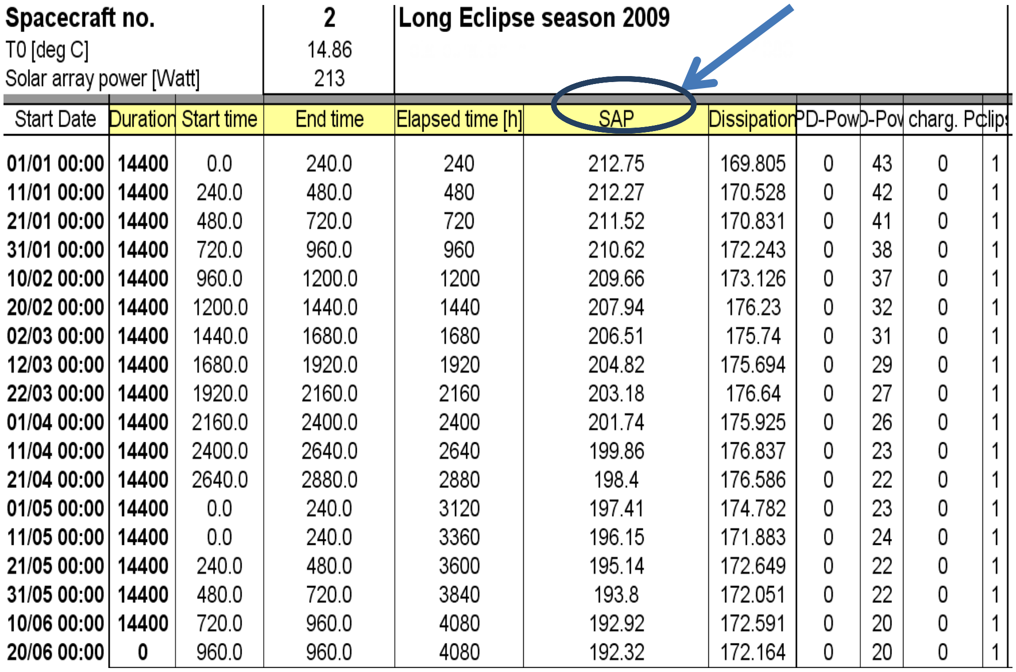
Figure 13: Eclipse seasons 2009-2012

Two analysis have been conducted, one in long scale, one in short scale. The first one, has been used more for a trend analysis and applied to the last 4 years. This is less precise and covers bigger periods (intervals of 10 days were chosen). The short scale analysis is more detailed and each change (e.g. in the IPD Power) is examined.

6.1.1 Long Scale analysis

The analysis in large-scale gave the possibility of understanding which are the main parameters that needed to be changed because the model is not simulating correctly.

The first parameter that has been changed is the Solar Array Power which was kept constant from the model; if a larger period is analysed, such as half an year, the value of the SAP changes significantly. For this reason a new calculation has been introduced, such that the SAP varies with the date, as can be seen in **Figure 14** (remember that the SAP is an important value for the calculation of the dissipation on board the spacecraft).



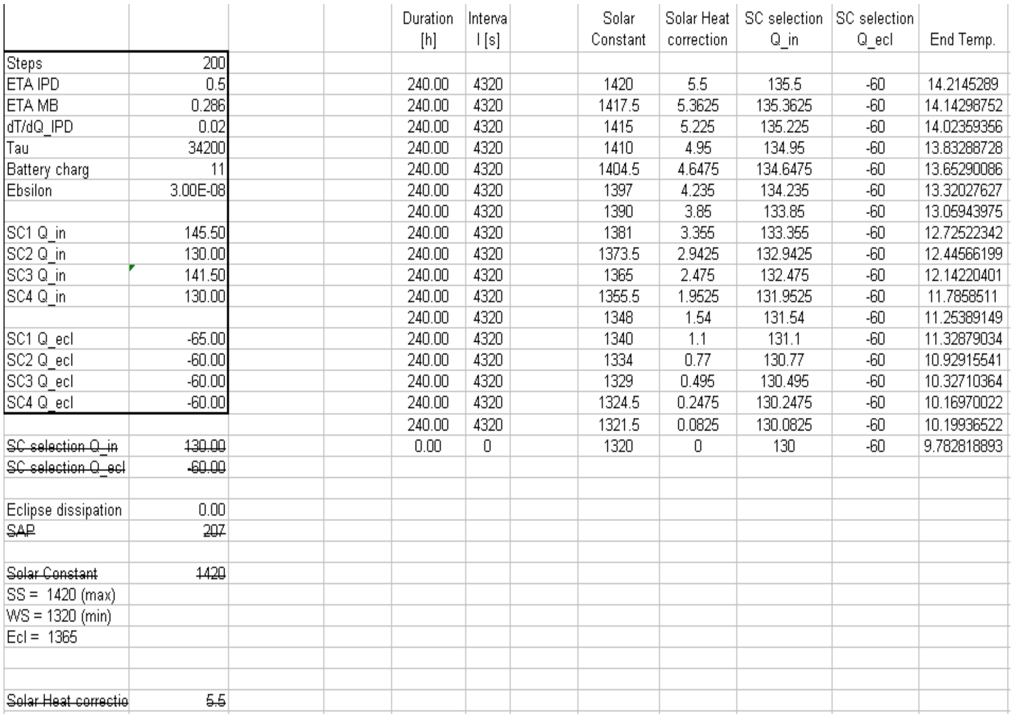
Spacecraft no.	**2**	**Long Eclipse season 2009**
T0 [deg C]	14.86	
Solar array power [Watt]	213	

Start Date	Duration	Start time	End time	Elapsed time [h]	SAP	Dissipation	PD-Pow	D-Pov	charg. Pc	clips
01/01 00:00	**14400**	0.0	240.0	240	212.75	169.805	0	43	0	1
11/01 00:00	**14400**	240.0	480.0	480	212.27	170.528	0	42	0	1
21/01 00:00	**14400**	480.0	720.0	720	211.52	170.831	0	41	0	1
31/01 00:00	**14400**	720.0	960.0	960	210.62	172.243	0	38	0	1
10/02 00:00	**14400**	960.0	1200.0	1200	209.66	173.126	0	37	0	1
20/02 00:00	**14400**	1200.0	1440.0	1440	207.94	176.23	0	32	0	1
02/03 00:00	**14400**	1440.0	1680.0	1680	206.51	175.74	0	31	0	1
12/03 00:00	**14400**	1680.0	1920.0	1920	204.82	175.694	0	29	0	1
22/03 00:00	**14400**	1920.0	2160.0	2160	203.18	176.64	0	27	0	1
01/04 00:00	**14400**	2160.0	2400.0	2400	201.74	175.925	0	26	0	1
11/04 00:00	**14400**	2400.0	2640.0	2640	199.86	176.837	0	23	0	1
21/04 00:00	**14400**	2640.0	2880.0	2880	198.4	176.586	0	22	0	1
01/05 00:00	**14400**	0.0	240.0	3120	197.41	174.782	0	23	0	1
11/05 00:00	**14400**	0.0	240.0	3360	196.15	171.883	0	24	0	1
21/05 00:00	**14400**	240.0	480.0	3600	195.14	172.649	0	22	0	1
31/05 00:00	**14400**	480.0	720.0	3840	193.8	172.051	0	22	0	1
10/06 00:00	**14400**	720.0	960.0	4080	192.92	172.591	0	20	0	1
20/06 00:00	**0**	960.0	960.0	4080	192.32	172.164	0	20	0	1

Figure 14: New calculation for the Solar Array Power (SAP)

More parameters were kept constant depending on the first date that was inserted as input. As such new rules have been created. For example the *solar constant* varies during one year and depending on it also the *solar* *heat correction* (correction on the solar flux determined with the telemetry). Two more parameters have been changed: SC Q_in and SC Q_ecl, which are the spacecraft consumption out of the eclipses and during eclipses. **Figure 15** shows for the period between 1st Jan 2009 and 20th Jun 2009 how the parameters have been adjusted: on the left bottom we can still see (strikethrough) the old parameters, that , in this case, were depending only on the first input, so they were referring to 1st Jan 2009 and kept constant. On the top right are listed the new columns with the parameters calculated depending on the different date. It can be seen, for example that the solar constant's value varies between 1420 and 1320.

The output of the model can be seen in **Figure 16**, where the blue line represents the model predictions, and the red line represents the telemetry. If we compare **Figure 16** and **Figure 12** we can now see that the model is finally matching the telemetry.



		Duration [h]	Interval [s]	Solar Constant	Solar Heat correction	SC selection Q_in	SC selection Q_ecl	End Temp.
Steps	200							
ETA IPD	0.5	240.00	4320	1420	5.5	135.5	-60	14.2145289
ETA MB	0.286	240.00	4320	1417.5	5.3625	135.3625	-60	14.14298752
dT/dQ_IPD	0.02	240.00	4320	1415	5.225	135.225	-60	14.02359356
Tau	34200	240.00	4320	1410	4.95	134.95	-60	13.83288728
Battery charg	11	240.00	4320	1404.5	4.6475	134.6475	-60	13.65290086
Ebsilon	3.00E-08	240.00	4320	1397	4.235	134.235	-60	13.32027627
		240.00	4320	1390	3.85	133.85	-60	13.05943975
SC1 Q_in	145.50	240.00	4320	1381	3.355	133.355	-60	12.72522342
SC2 Q_in	130.00	240.00	4320	1373.5	2.9425	132.9425	-60	12.44566199
SC3 Q_in	141.50	240.00	4320	1365	2.475	132.475	-60	12.14220401
SC4 Q_in	130.00	240.00	4320	1355.5	1.9525	131.9525	-60	11.7858511
		240.00	4320	1348	1.54	131.54	-60	11.25389149
SC1 Q_ecl	-65.00	240.00	4320	1340	1.1	131.1	-60	11.32879034
SC2 Q_ecl	-60.00	240.00	4320	1334	0.77	130.77	-60	10.92915541
SC3 Q_ecl	-60.00	240.00	4320	1329	0.495	130.495	-60	10.32710364
SC4 Q_ecl	-60.00	240.00	4320	1324.5	0.2475	130.2475	-60	10.16970022
		240.00	4320	1321.5	0.0825	130.0825	-60	10.19936522
~~SC selection Q_in~~	~~130.00~~	0.00	0	1320	0	130	-60	9.782818893
~~SC selection Q_ecl~~	~~-60.00~~							
Eclipse dissipation	0.00							
~~SAP~~	~~207~~							
~~Solar Constant~~	~~1420~~							
SS = 1420 (max)								
WS = 1320 (min)								
Ecl = 1365								
~~Solar Heat correctio~~	~~5.5~~							

Figure 15: Modification of the parameters in the original model. On the left bottom the old parameters (strikethrough), on the top right the column of the new parameters,

calculated depending on the different input inserted as a date. The period covered is between 1st Jan 2009 and 20th Jun 2009

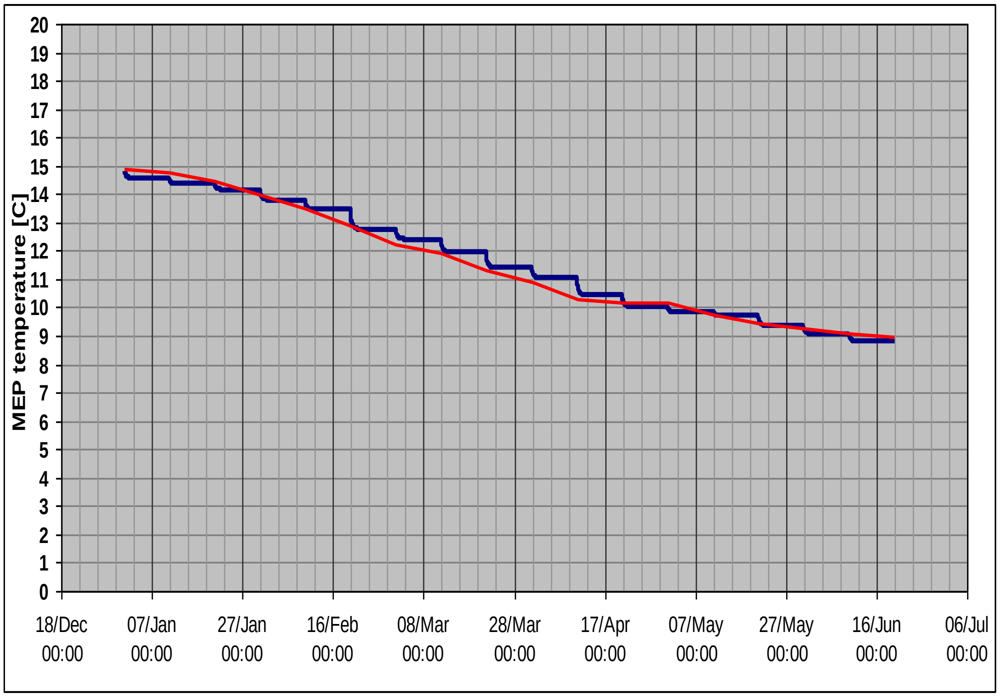


Figure 16: SC 3, Jan-Jun 2010 using the model with the modifications. The blue line represents the model predictions, the red line represents the telemetry

6.1.2 Short Scale analysis

After the model has been improved, it has been applied to short intervals. In particular each single orbit has been examined, i.e. a period of 54 hours, from apogee to apogee (otherwise the radiation from Earth when at perigee should have been taken into account). The orbits have been chosen per different periods of the year.

The results show that during Spring/Fall, the simulation follow the telemetry (**Figure 17**), while during summer the model simulates about 0.5°C more than the real telemetry (**Figure 18**), and during winter about 0.5°C less than the real telemetry (**Figure 19**). This might be linked to the fact that the model has been developed only for a specific period (Spetember).

Note that we have a gap in the telemetry during the eclipse. This is the reason why the red line is not continuous but it presents an interruption exactly during the eclipse time.

Moreover it should be pointed that the model over-estimates the eclipse (i.e. the temperature after the eclipse results lower than what in reality it is).

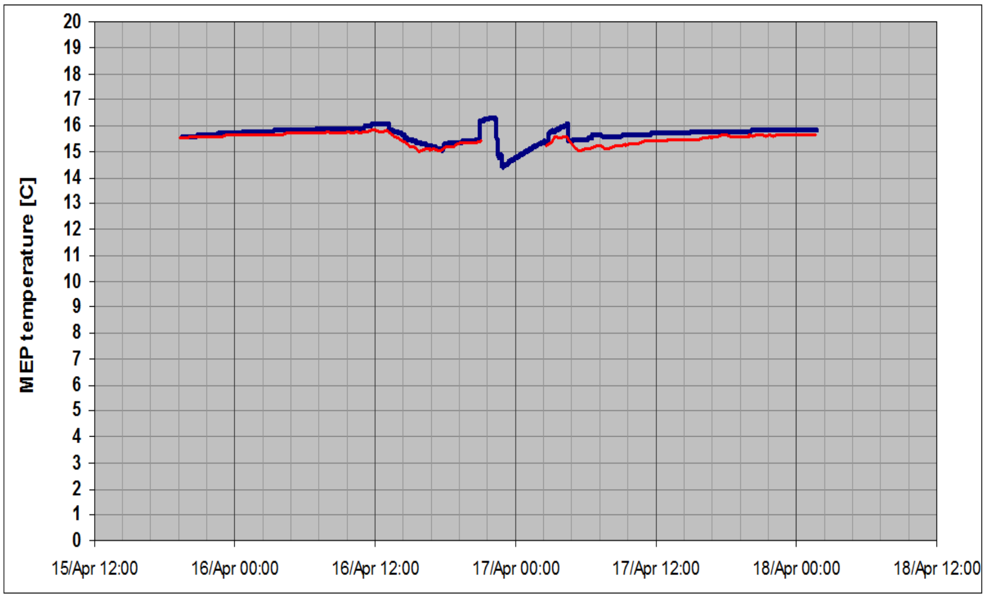


Figure 17: Small Scale Analysis. The blue line represents the model prediction, the red line represents the real telemetry. During autumn/spring The model seems to predict very well the telemetry.

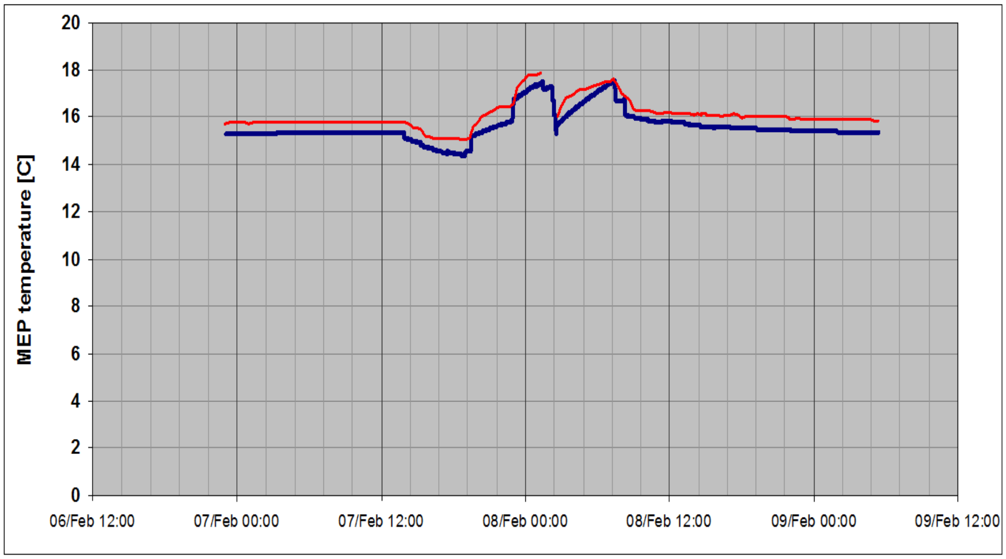


Figure 18: Small Scale Analysis. The blue line represents the model prediction, the red line represents the real telemetry. During winter the telemetry results about 0.5 C higher than the temperature predicted by the model

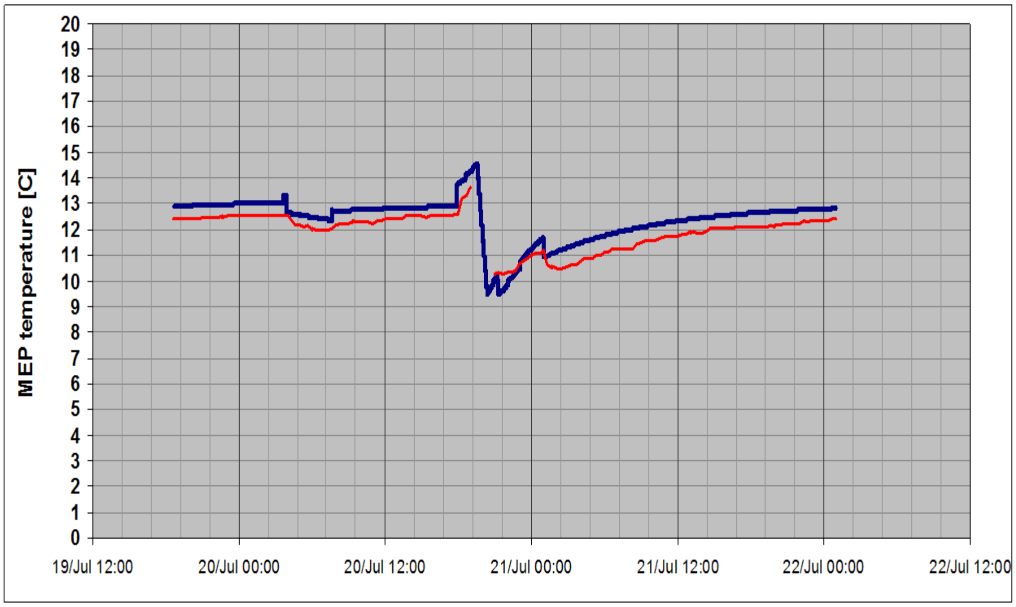


Figure 19: Small Scale Analysis. The blue line represents the model prediction, the red line represents the real telemetry. During summer the telemetry results about 0.5 C lower than the temperature predicted by the model

7. Thermal Strategy

7.1 Trend Analysis

Before making the predictions for the long eclipse season of July- August 2012, the first step is to analyse the behaviour of the spacecraft for the last four years starting from January 2009 up to March 2012. This study was used in order to understand better the operating conditions of the spacecraft (e.g. temperature, IPD, SAP) and to do a trend analysis from the last years. Afterwards the data are fitted in the model to verify that the latter is still valid and can be considered reliable for the following predictions.

In order to make this study, six orbits for each spacecraft have been chosen, using the eclipses of the type “no battery”. In particular three different approach were used:

- Case 1: pre and post eclipse passes closed to eclipse
- Case 2: pre eclipse pass several hours before eclipse
- Case 3: post eclipse pass several hours after eclipse.

The thermal strategy includes the switching off of the spacecraft during the last pass before the eclipse and switch it on at the first pass after the eclipse. The study of the different cases as previously divided, is used in order to understand the advantages and disadvantages of having the pass close or far from the eclipse (both the pre and the post eclipse passes).

7.2 EPD 80 W

The first important result can be deducted when studying the cases with the post eclipse pass far from the eclipse. When plotting together the telemetry with the temperature predicted from the model, a large deviation after the eclipse appeared after each eclipse. In particular, the model was predicting a temperature recovery which was much faster than in the reality. From the model it was evident that there was a dissipation just after the eclipse that needed to be taken into account.

When switching off the spacecraft, this will cause a reboot of the CTU, and the default logics are executed automatically. Among these the EPD AUTO ON: whenever the IPD current reaches 5.2 A, which corresponds to about 145 W of dissipation this function is enabled. The goal of this function is to avoid internal overheating of the spacecraft and of the IPDs.

When the systems restart after the power down during the eclipse, most of the logics are reset to their default values. Among these the EPD AUTO ON function. In particular it happens that whenever the IPD current reaches 5.2 A, which corresponds to about 145 W of dissipation the EPD dissipate 80 Watts, subtracting them to the spacecraft . The goal of this function is to avoid internal overheating of the spacecraft and of the IPDs.

Due to the reboot after the eclipse, it is not possible to disable permanently this function, which means that after the eclipses there is the risk that the function is enabled and remains as such until it is disabled with a command sent from ground during the following pass. This is a crucial point which leaded to the choice of the post-eclipse pass as close as possible to the eclipse itself, such that the EPD Auto ON function can be disabled as soon as possible (higher priority is given to the coldest spacecraft).

Figure 20 shows the differences in the MEP temperature when the EPD 80W are not taken into account after eclipse (upper plot) or when the model considers the influence of the 80W dissipation (lower plot). In the two graphs the blue line represents the temperature predicted by the model, while the red line is the telemetry collected from the spacecraft. It is evident that without taking into account the 80 W dissipation, the temperature after the eclipse would start to increase immediately. Instead, in the lower plot it is shown that after the eclipse exit, the temperature continues to decrease until the moment when the contact with the spacecraft is established and the EPD Auto ON function disabled (the temperature starts to increase).

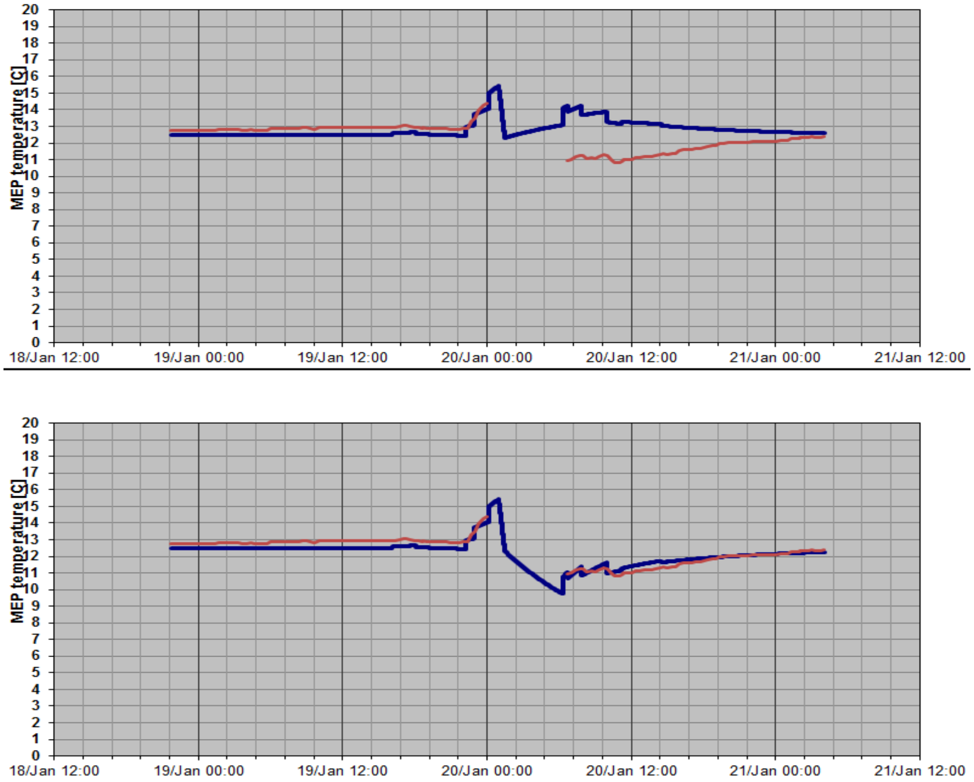


Figure 20: Eclipse 19th Jan 2012, SC3. The upper plot doesn't take into account the EPD 80 W after the eclipse. In the lower plot the EPD 80W AUTO ON function is taken into account. The blue line is the temperature predicted by the model, the red line is the telemetry.

7.3 HPA and Heater E

As mentioned above, the HPA is a critical unit in the spacecraft, important for the communication with the satellite. This unit presents a very high dissipation, which brought to mount the two HPAs (main and redundant) on a dedicated radiator for the heat rejection. A software controlled heater circuit is used to keep the HPA in the range of allowed temperatures and a thermostat controlled heater circuit serves as back-up in special conditions such as during power critical eclipses.

The nominal temperature is between 18°C and -5°C , depending on the mode in which the satellite is operating. For the HPA in non-operational conditions, the qualification temperature (i.e. the minimum temperature that the device can suffer) is -50°C, and the acceptance temperature (i.e.

the temperature at which the device has been tested) is -40℃. Regarding the cold start, the qualification temperature is -40℃ and the acceptance temperature is -30℃.

In normal operations the drop below the acceptance temperature is prevented thanks to the heater F which triggers at -25℃. Nevertheless this protection is not active during eclipses when there are no Thermal Control Subsystem (TCS) operations.

By studying the simulations of the HPA behaviour done in 2006, and making new ones depending on the new temperatures at which the satellites are operating, an analysis of the HPA temperature has been conducted.

In particular the study was centred on the advantages that the use of the dedicated Heater E could give during the eclipses operations.

Figure 21 shows the temperature variation of the HPA during the eclipses if the Heater E is used (blue line) or if the Heater E is not used (red line). In the simulations this heater is used to warm the HPA up before the eclipse, such that it enters the shadow with higher temperature and dissipates the heat during the eclipsed period. In particular when the Heater E is used, the HPA is operating in High Power Mode (HPM), while if the Heater E is not used, then the HPA is OFF. From the graph it is evident the difference of the temperatures at the beginning of the plot, while when increasing in time, the difference decreases considerably. During the long eclipse season the eclipses reach a duration of about 2hrs and 10 minutes, which means about 7620 seconds. If we analyse the plot, when in correspondence of 7620 seconds, the difference between the two curves is about 5℃. Despite the fact that 5 degrees could be an advantage for the HPA temperature after the eclipse, nevertheless it should be taken into account that the use of the Heater E before entering eclipse has a major impact on the power dissipation (this heater has a consumption of 24 W) which will contribute to lowering the temperature considerably before the eclipse itself, and also the unnecessary need of new procedures that would increase the workload of the Flight Control Team (FCT). According to these simulations it has been decided to not use the Heater E for the long eclipse season 2012 and to keep the HPA OFF. However, the study showed that the heater E pre-heating approach could be useful in future eclipse seasons to avoid the HPA reaching critical temperatures.

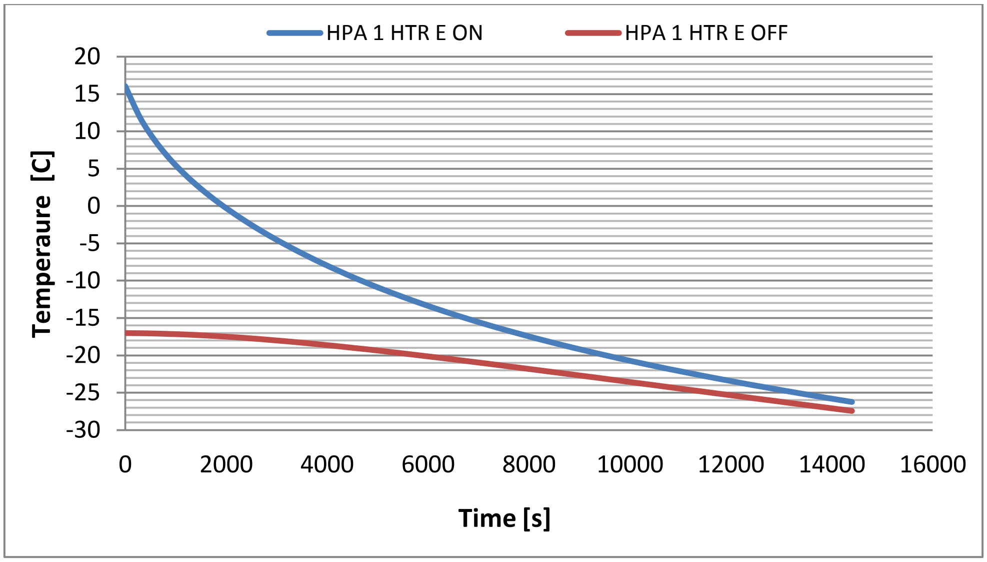


Figure 21: HPA behaviour when the heater E is used (blue line) and when the heater is not used (red line) during eclipses operations

7.4 Tank pre-heating

The pre-heating, is a strategy to warm up as much as possible the spacecraft before entering in eclipse. Nevertheless there are some limitations due to the fact, for example, that the fuel available is much less than at the beginning of the mission, thus less heat can be stored and released during the eclipse.

7.4.1 Anomaly 19th June 2011

The 19th of June 2011, during the long eclipse season, an anomaly occurred in spacecraft 4. The causes of the anomaly are nowadays still under investigation by the power engineers. The CTU boot at eclipse exit and a main bus under-voltage occur, which leaded to CTU OFF (the Subsystem Reconnection Logic (SRL) didn’t allow the Latch Current Limiter (LCL) to switch on the CTU). This last step could be expected, and multiple reboots have happened before. The anomaly is the fact that the CTU remained OFF.

After several tries, the anomaly has been solved by switching off the RTUs and then RTUB ON, with finally the AOS (Acquisition of Signal) [6].

A deeper explanation of the anomaly is beyond the goal of this thesis, but thanks to the thermal simulations it was proved that the EPD 80 W was on, causing the cooling down and preventing the SRL to sonnet the CTU LCLs.

Furthermore, when studying the anomaly with the thermal model, this gave the possibility of understanding the effect of the tank pre- heating on the average MEP temperature. As a matter of fact, due to the anomaly , and to avoid further problems on the following eclipses, the tank pre-heating strategy was immediately applied. The objective is the warm tanks to release heat during the eclipse; on the other hand when using the heaters, the spacecraft dissipates power at the expenses of the MEP temperature.

The effect has been discovered because, when comparing the telemetry of the event, and the predicted temperature from the model, a very large discrepancy was registered. From **Figure 22**, on the top graph we see that the model would predict a fast increase of the temperature after the eclipse: that is the one that we would register if no heating would be done. The lower graph instead, shows how the model predict the temperature if we consider the dissipation during the heating (the blue line is the model prediction, and the red line is the telemetry collected from the spacecraft). In particular, in the model, the dissipation is simulated by inserting the dissipated power as if it was in the EPD, to simulate it as a loss. Note that each heater dissipate about 20 Watts and two tank heaters are used.

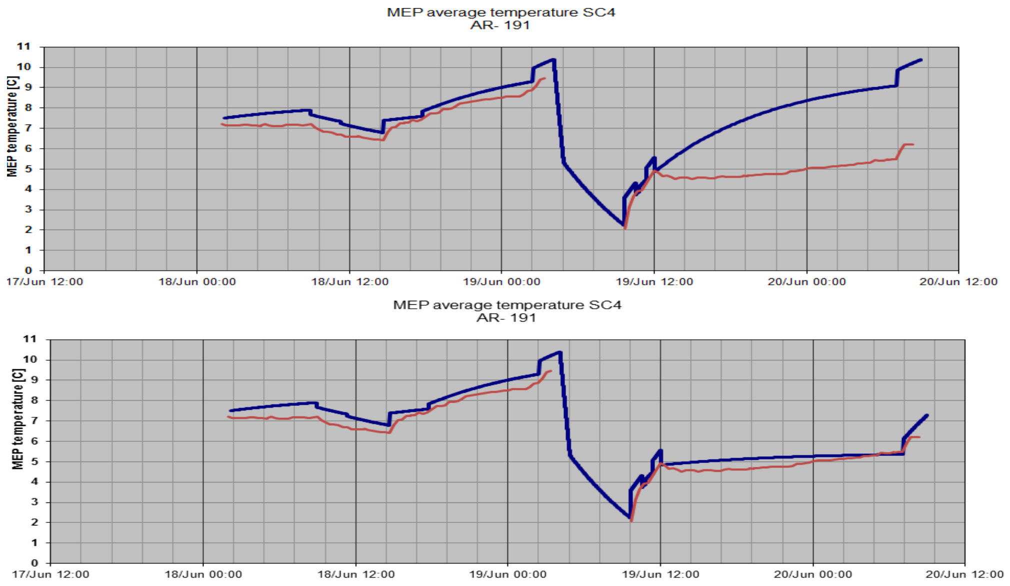


Figure 22: Anomaly 19th June 2011. The effect of the tanks pre- heating is clear in the second part of the graphs, and is simulated in the lower graph (blue line is the temperature predicted from the model, and the red line is the telemetry)

7.4.2 Tests 2012

In order to understand the capacitance of the tanks a few tests have been conducted during normal operations. Tests have been conducted on the oxidiser tanks and the fuel tanks. The oxidiser ones showed a larger capacitance than the fuel ones: this implies that the time used by the oxidiser to warm up is larger (about 36 hours) than the one for the fuel (about 34 hours), but on the other hand the capability of retaining the heat is larger for the oxidiser rather than for the fuel.

Nevertheless, as shown when studying the anomaly of 19th June 2011, the heating implies consequences such as the power dissipation, which will lead to a lower IPD and to a lower MEP temperature. As a matter of fact, the tests show that the MEP loses about 2 degrees during the entire heating time. Later, when switching OFF the heaters, the MEP temperature recovers to the initial value in about 12 hours, and then it gains one more degree from the heat released from the tanks.

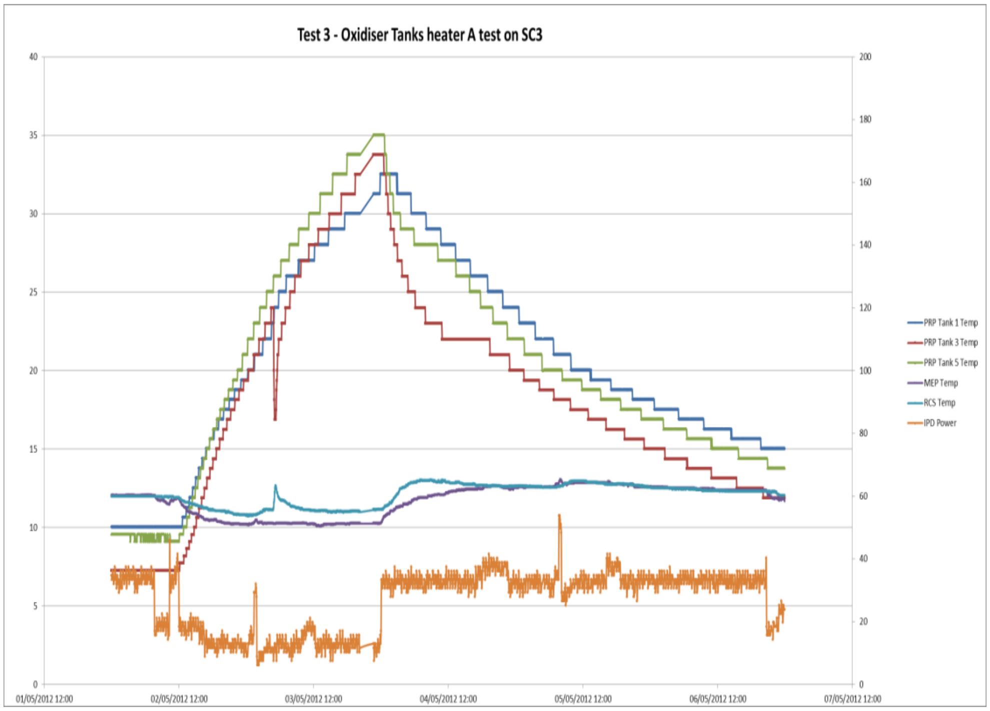
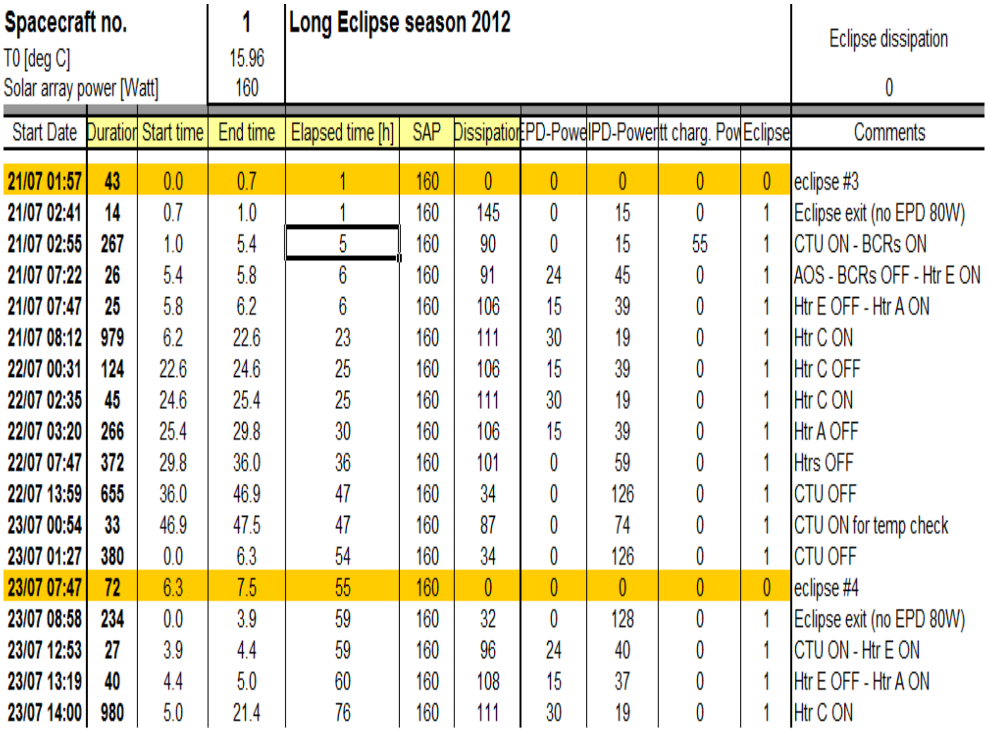


Figure 23: Oxidiser tanks heater A test on spacecraft 3

Figure 23 shows the results from the test conducted on the oxidiser tank on spacecraft 3 using the heater A during May 2012. From the graph ,in orange it is shown the IPD power that decreases when the heater is operating and then goes back to the nominal value when the heating ends. The violet line shows instead the MEP temperature: the graph shows that it decreases when in correspondence of the heating and increases gaining one more degree when the heater is OFF. The dark blue, red and green lines represent the temperature of the tanks: it increases when the heater A is used and then they release the heat: the warming up is much faster and then the release is slower, which is good for keeping warm the spacecraft for a longer time. From the plot we can also see a spike representing a temperature drop: this can be explained because of the movements of the cold propellant along the pipes between the tanks.

7.5 The strategy

The strategy that is applied for the long eclipse season 2012 is the result of all the considerations that have been explained above.



Spacecraft no. 1 **Long Eclipse season 2012**
T0 [deg C] 15.96
Solar array power [Watt] 160

Eclipse dissipation
0

Start Date	Duration	Start time	End time	Elapsed time [h]	SAP	Dissipation	EPD-Powe	IPD-Power	tt charg. Pow	Eclipse	Comments
21/07 01:57	**43**	0.0	0.7	1	160	0	0	0	0	0	eclipse #3
21/07 02:41	**14**	0.7	1.0	1	160	145	0	15	0	1	Eclipse exit (no EPD 80W)
21/07 02:55	**267**	1.0	5.4	5	160	90	0	15	55	1	CTU ON - BCRs ON
21/07 07:22	**26**	5.4	5.8	6	160	91	24	45	0	1	AOS - BCRs OFF - Htr E ON
21/07 07:47	**25**	5.8	6.2	6	160	106	15	39	0	1	Htr E OFF - Htr A ON
21/07 08:12	**979**	6.2	22.6	23	160	111	30	19	0	1	Htr C ON
22/07 00:31	**124**	22.6	24.6	25	160	106	15	39	0	1	Htr C OFF
22/07 02:35	**45**	24.6	25.4	25	160	111	30	19	0	1	Htr C ON
22/07 03:20	**266**	25.4	29.8	30	160	106	15	39	0	1	Htr A OFF
22/07 07:47	**372**	29.8	36.0	36	160	101	0	59	0	1	Htrs OFF
22/07 13:59	**655**	36.0	46.9	47	160	34	0	126	0	1	CTU OFF
23/07 00:54	**33**	46.9	47.5	47	160	87	0	74	0	1	CTU ON for temp check
23/07 01:27	**380**	0.0	6.3	54	160	34	0	126	0	1	CTU OFF
23/07 07:47	**72**	6.3	7.5	55	160	0	0	0	0	0	eclipse #4
23/07 08:58	**234**	0.0	3.9	59	160	32	0	128	0	1	Eclipse exit (no EPD 80W)
23/07 12:53	**27**	3.9	4.4	59	160	96	24	40	0	1	CTU ON - Htr E ON
23/07 13:19	**40**	4.4	5.0	60	160	108	15	37	0	1	Htr E OFF - Htr A ON
23/07 14:00	**980**	5.0	21.4	76	160	111	30	19	0	1	Htr C ON

Figure 24: Thermal model. Long eclipse season 2012. Eclipse 21th July, Spacecraft 1

Figure 24 is a snapshot from the model that shows the "strategy structure". What is important to understand can be read in the column of the comments. The model starts with the eclipse entry time. The next step is to take into account the EPD AUTO ON function (see above for the description). In this case the 145W of power are not reached, thus the EPD 80 W are not dissipated. As soon as there is acquisition of signal (AOS), the command for switching ON the heater E is sent (note that this is the heater for the HPA, but it is used after the eclipse to recover the temperature and not before the eclipse to warm up). After that the heaters A and C are switched ON. It can be noticed that there might be subsequent ON and OFF of the heaters (in this case of Htr C), this is due to the fact that above a certain threshold the heaters are switched off from an automatic logic on board the spacecraft, thus they are off before the off command is sent from ground. When we are about 24 hours before the following eclipse the heaters are switched off (remember that the pre-heating causes power dissipation and decreasing of temperature, and it is needed 12 hours for the MEP to recover). During the last pass before the eclipse, the CTU is switched off. Indeed it has been demonstrated with the trend analysis that by switching off the CTU (thus all the units in the spacecraft) the power dissipation is lower which make the MEP temperature increase. According to this it is preferable to switch it off as soon as possible in order to guarantee an higher temperature. Moreover two tests have been conducted before two eclipses for spacecraft 1 and spacecraft 3 (the test on spacecraft 1 is the one represented in **Figure 24**) : after switching off the CTU about 24 hours before the eclipse, during another pass, a few hours before the eclipse, the satellite is switched ON in order to get the telemetry and check what are the operating conditions of the satellite. In this cases, at the end of the pass again the command to switch off the CTU is sent and as such the satellite will proceed until the new pass after the eclipse when it will be recovered.

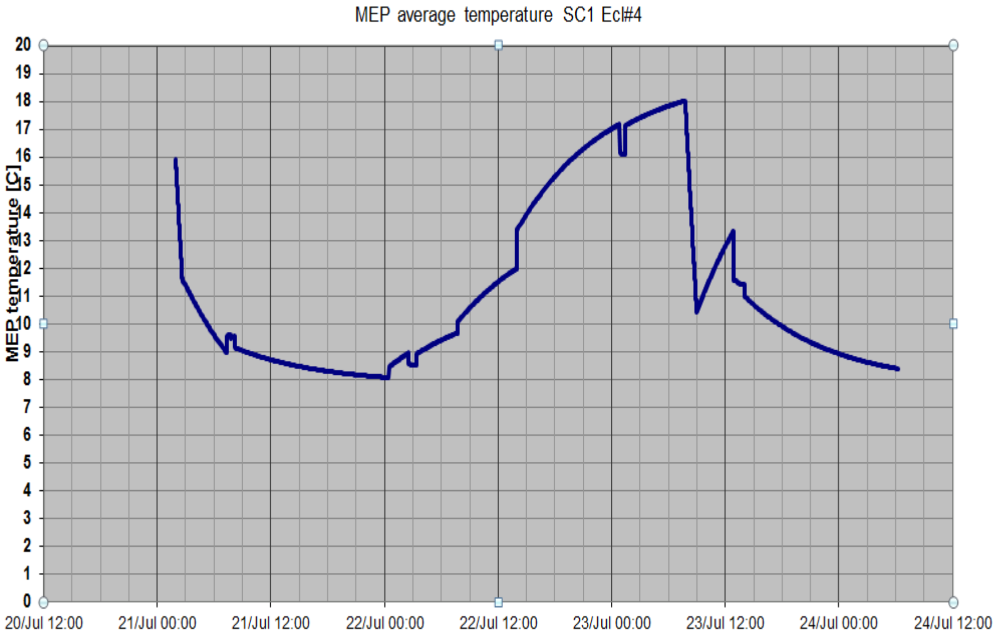


Figure 25: Expected behaviour of the MEP temperature. Spacecraft 1, 21th July 2012

Figure 25 shows the expected MEP temperature from the model regarding the eclipse analysed according to the input in **Figure 24**. As expected the temperature decreases during the eclipse reaching a minimum value of about 8℃. The temperature is recovering and thanks to the heaters is also gaining some degrees before the following eclipse. The temperature has a little drop that corresponds to the period in which the CTU is switched on in order to check the telemetry. Afterwards there is again an eclipse and we see the drop of the temperature and in the same way as before the trend behaviour is repeated.

It should be noticed that this behaviour is similar but not the same for all the spacecraft and not for every eclipse (e.g. depending on the length of the eclipse, the recovery of the MEP temperature can be lower than the one showed in **Figure 25**, and especially during the most critical eclipses – the longest ones- , the temperature is not able to recover completely and it will be lower for each sequent eclipse).

The very critical power conditions (e.g. SAP) and the need of thermal recovery is such that all the available power is used for warming up the spacecraft. As a consequence the entire payload is switched off in all the spacecraft 56 hours before the first eclipse (only exception is spacecraft 2, where the pre-heating is not necessary and the payload is switched off only 12 hours before the first eclipse). For the entire eclipse season (about 21 days) the payload will be off and it will be switched ON only during the first pass after the last eclipse (the timing will depend on the availability and visibility of the ground station).

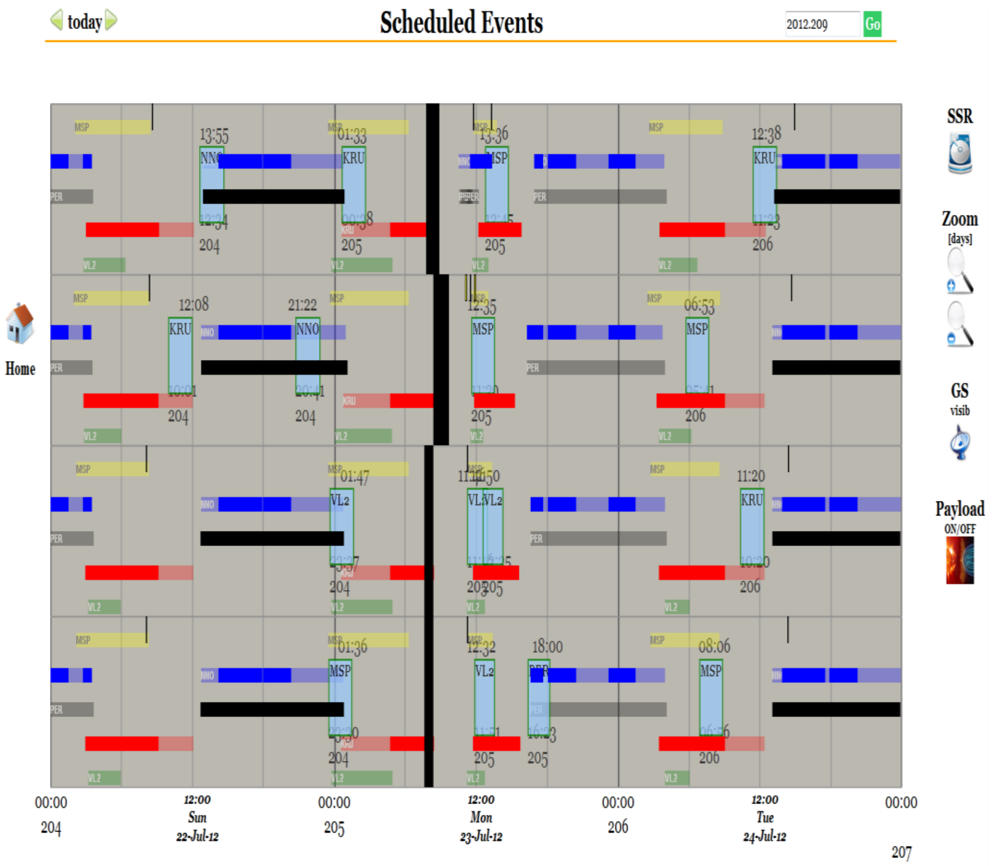


Figure 26: Cluster scheduled event timeline

Figure 26 shows a snapshot of the CLUSTER web where it is possible to follow the events (e.g. eclipses, ground station availability) affecting the four spacecraft. In particular the black vertical line represents the eclipse, and the blue boxes are the passes booked for the satellites. The other horizontal lines represent the ground station visibility and also when they are already booked (dark colour).

8. Comparison with the telemetry

After the eclipses the retrieval of the telemetry is done in order to monitor the conditions of the spacecraft. In particular the parameters used for the predictions has been retrieved and analysed (e.g. IPD power, EPD power, MEP temperature, SAP, battery charging).

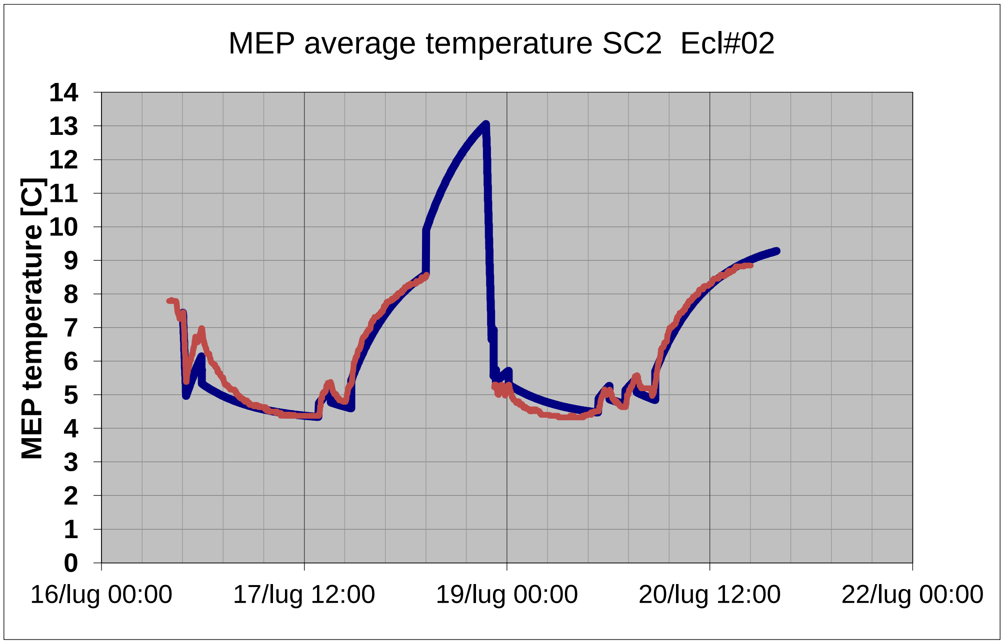


Figure 27: Sc2 Eclipse 19th July 2012. In blue the temperature predicted by the model, in red the temperature from the telemetry

Figure 27 shows the results regarding SC2 for the eclipse of 19th July 2012. The eclipse is a NO BATTERY. The blue line is the temperature predicted by the model, while the red line is the temperature from the telemetry. From the plot we can see that the telemetry is following quite well the predictions done with the model.

Nevertheless a particular attention should be given at the two tests done for spacecraft 1 (23rd July) and spacecraft 3 (28th July). The two tests show that the temperature before the eclipse doesn't reach the one predicted by the model, but it is about two degrees less. As a consequence, after the eclipse the temperature is also lower than expected, although the discrepancy is less than the one at eclipse entry: now the telemetry is about 0.5 degrees lower than the predicted temperature **(Figure 28**).

A few deviation have been registered also after the eclipse when the temperature tends to decrease a bit more than in the predictions. Normally the discrepancy is visible only at the beginning and after a few minutes the two temperatures (the predicted one and the real one) tends to match again (**Figure 29**).

In general, apart from these discrepancies, the telemetry matches quite well the predictions done with the Excel model.

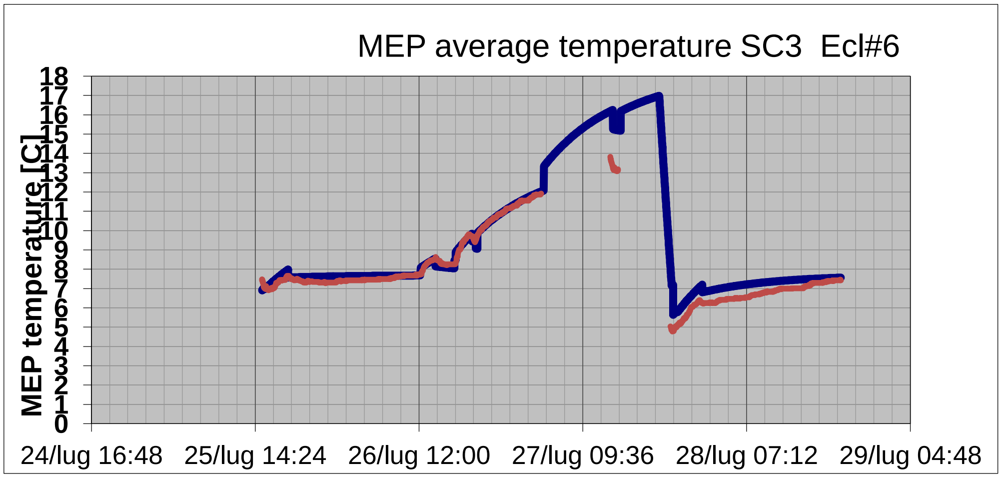


Figure 28: SC3 eclipse 27th July 2012. The spacecraft has been switched on for collecting the telemetry.

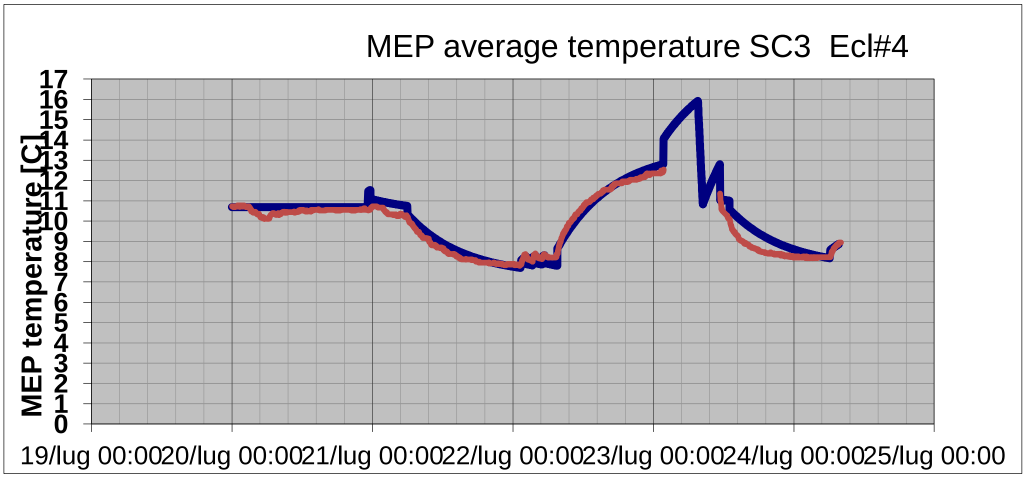


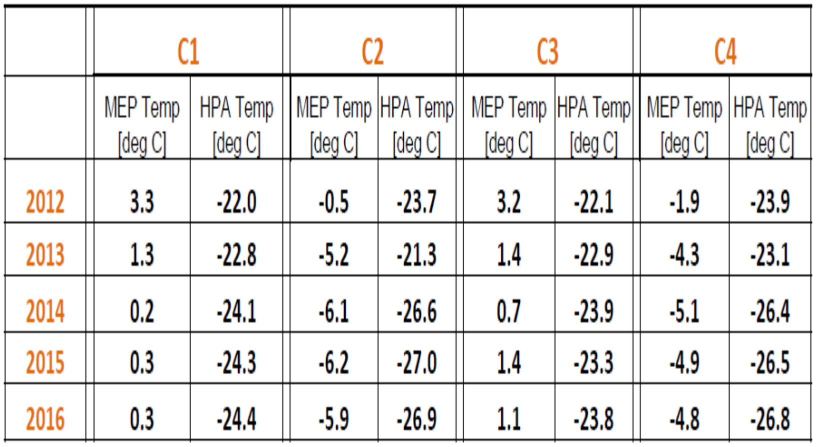
Figure 29: SC4 eclipse 22nd July 2012. After the eclipse the temperature decreases faster than the one predicted by the model. After a while the two temperatures match again.

9. Predictions 2012-2016

The 27th June 2012 the CLUSTER FCT presented the Mission Extension Operations Review (MEOR) with the forecast up to 2016.

The study of the current condition and the orbit evolution are the base for the predictions up to 2016. First of all it should be considered that the arrays are becoming more temperature sensitive and during perigee passage a power drop require TX&HPA off for about one hour. The collision risk with debris and other spacecraft is decreasing. The eclipse seasons are becoming shorter, although the long eclipses will become longer. The change in orbit is characterised by the decreasing of the height of the apogee and thus an improvement of the link budget. The visibility from the ground stations on the northern hemisphere (e.g. Kiruna) is improving with improved high bit rate dumps (100% from 2012 to 2016).

The MEP temperature model was used to predict the lowest temperature that will be reached during eclipse seasons. The results of the MEP were used to estimate also the HPA temperature, that is the most critical unit and needs to be monitored accurately. **Table 1** shows the predictions for the MEP and HPA temperature up to 2016 (in particular the HPA temperature is still within the acceptance limits).



	C1		C2		C3		C4	
	MEP Temp [deg C]	HPA Temp [deg C]	MEP Temp [deg C]	HPA Temp [deg C]	MEP Temp [deg C]	HPA Temp [deg C]	MEP Temp [deg C]	HPA Temp [deg C]
2012	3.3	-22.0	-0.5	-23.7	3.2	-22.1	-1.9	-23.9
2013	1.3	-22.8	-5.2	-21.3	1.4	-22.9	-4.3	-23.1
2014	0.2	-24.1	-6.1	-26.6	0.7	-23.9	-5.1	-26.4
2015	0.3	-24.3	-6.2	-27.0	1.4	-23.3	-4.9	-26.5
2016	0.3	-24.4	-5.9	-26.9	1.1	-23.8	-4.8	-26.8

Table 1: MEP and HPA temperature predictions up to 2016

Regarding the payload it is expected that it will continue to operate nominally without significant degradation. Enough fuel will make manoeuvres and routine slews possible up to 2016.The SAP evolution can be seen in **Figure 9** which looks promising up to 2016.

10. Results

In the following the results for the four satellites will be shown. In all the graphs, the blue line will represent the temperature predicted by the model , and in red the temperature from the telemetry collected by the spacecraft. Note that the eclipses' numbers are in agreement with the indications given in **Figure 8.**

10.1 SC 1

Spacecraft 1 is the second satellite, after spacecraft 2 entering the long eclipse season 2012, starting the 21st July 2012 at 01:57:40 and experiencing the last eclipse the 08th August 2012 at 01:56:49, for a total of nine eclipses. Despite the fact that it was not expected to be in very critical conditions, this satellite is often cooler than expected from the model predictions, although the thermal strategy applied can be considered successful.

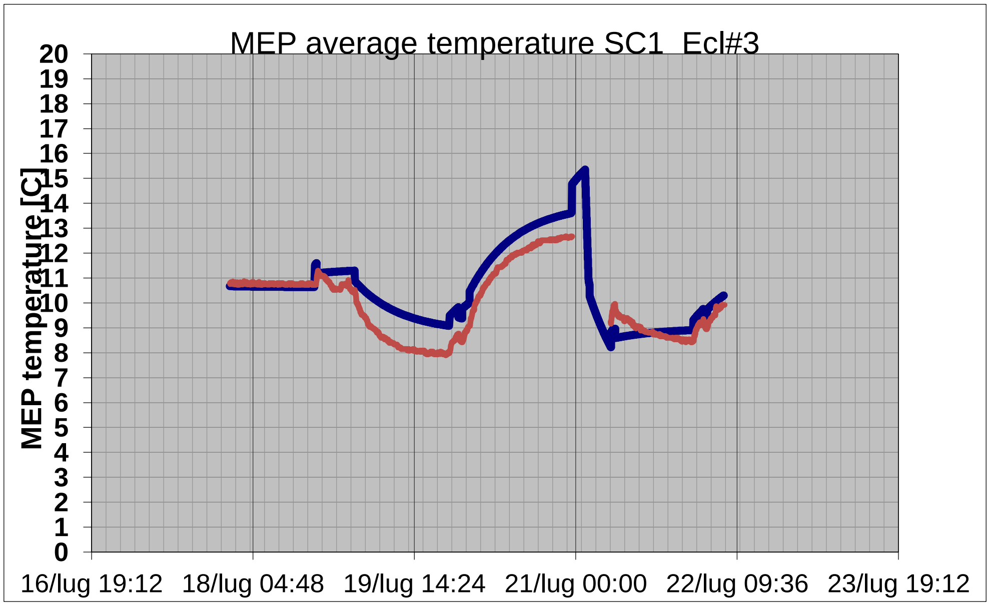


Figure 30: SC 1, Eclipse # 3, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

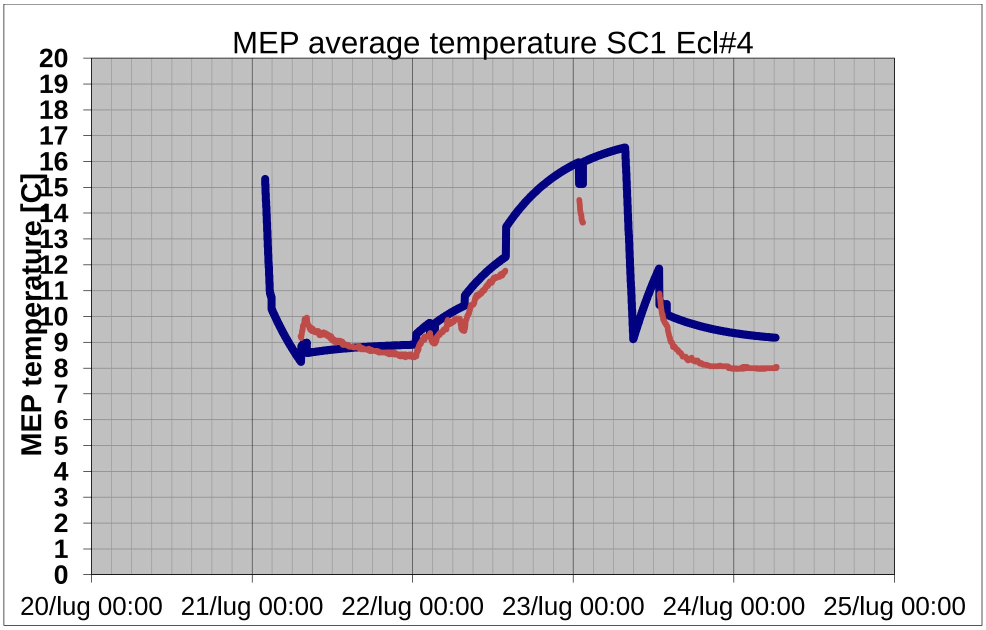


Figure 31:SC 1, Eclipse # 4, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

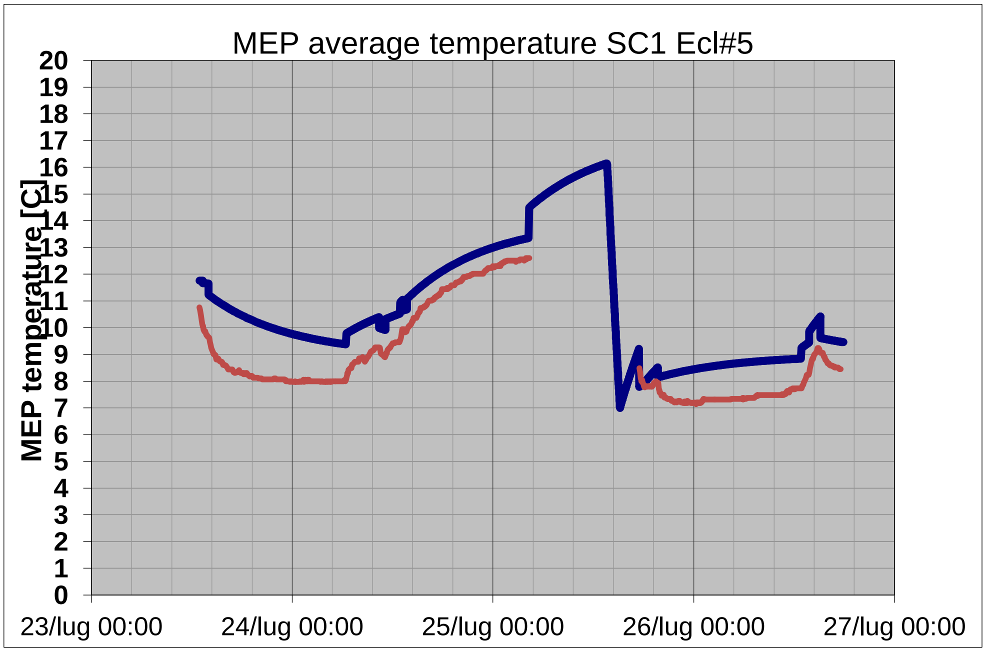


Figure 32:SC 1, Eclipse # 5, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

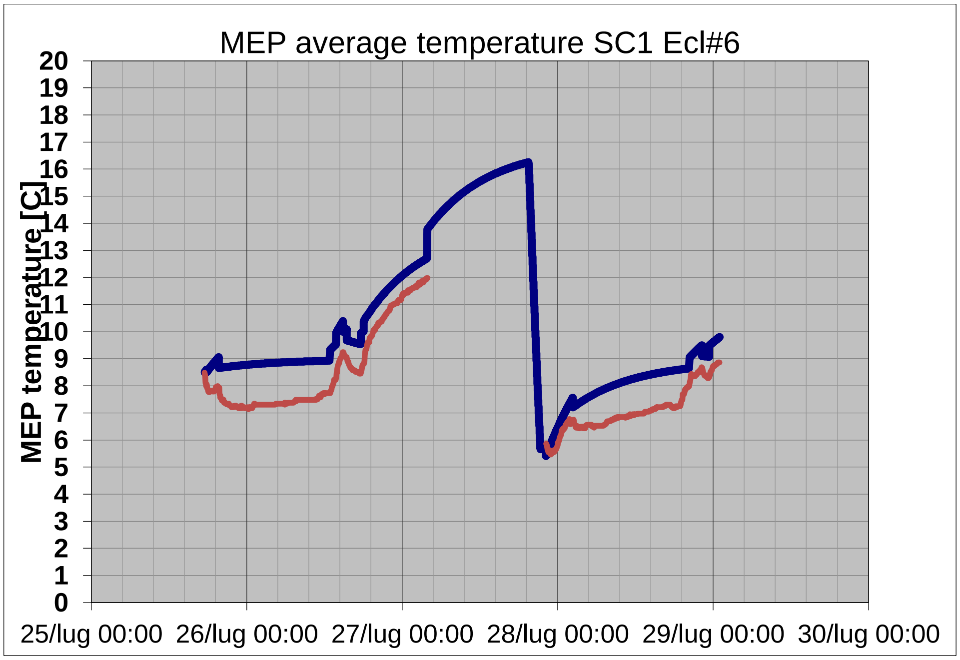


Figure 33:SC 1, Eclipse # 6, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

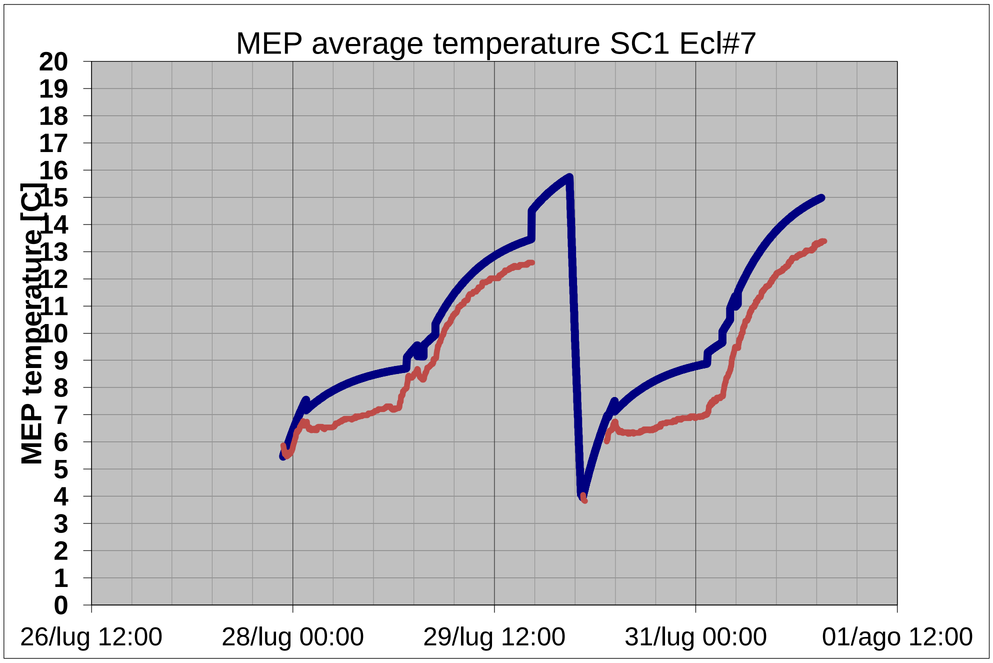


Figure 34:SC 1, Eclipse # 7, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

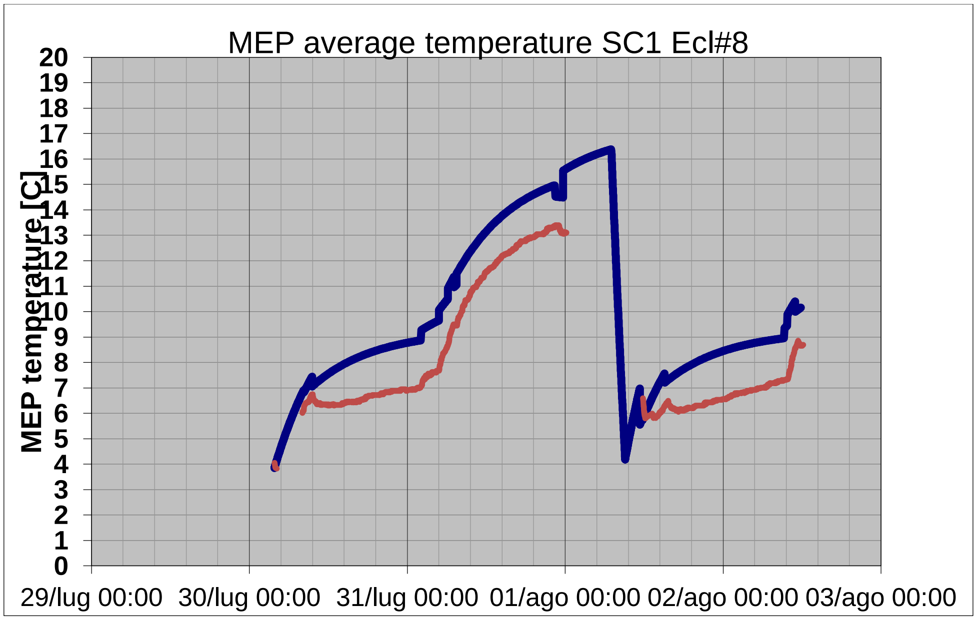


Figure 35:SC 1, Eclipse # 8, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

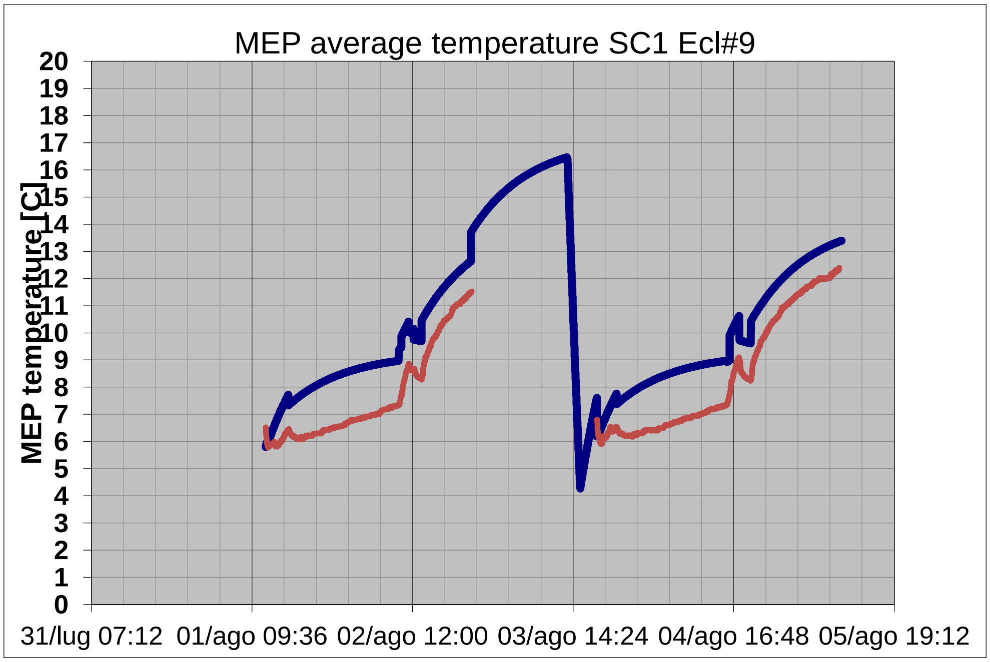


Figure 36:SC 1, Eclipse # 9, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

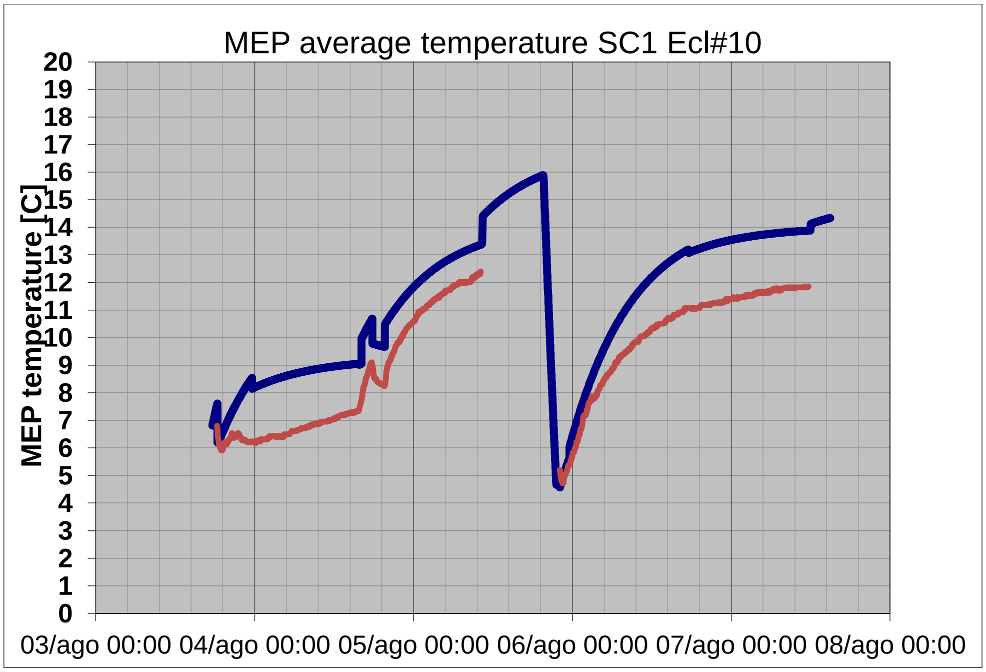


Figure 37:SC 1, Eclipse # 10, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

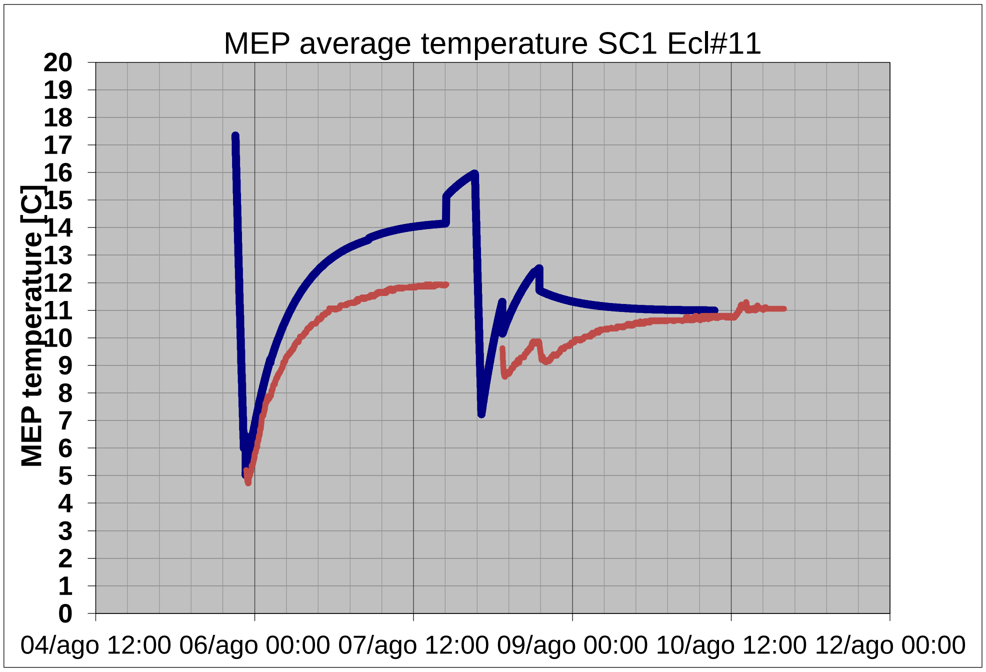


Figure 38:SC 1, Eclipse # 11, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

10.2 SC 2

Spacecraft 2 is the first spacecraft entering in eclipse. Furthermore it is the only one where three batteries are used up to the first eclipse. After the first eclipse then the other ones are all of the type NO BATTERY. The predictions from the model are the ones that match in the best way the telemetry taken from the spacecraft (compared to the simulations of the other satellites). The spacecraft experiences eleven eclipses, starting the 16th July 2012 and ending the 080th August 2012.

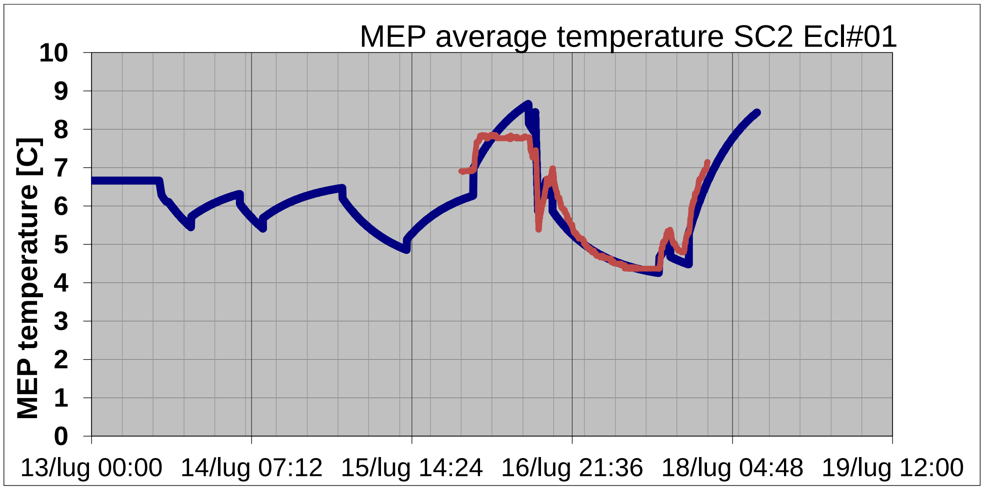


Figure 39: SC 2, Eclipse # 1, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

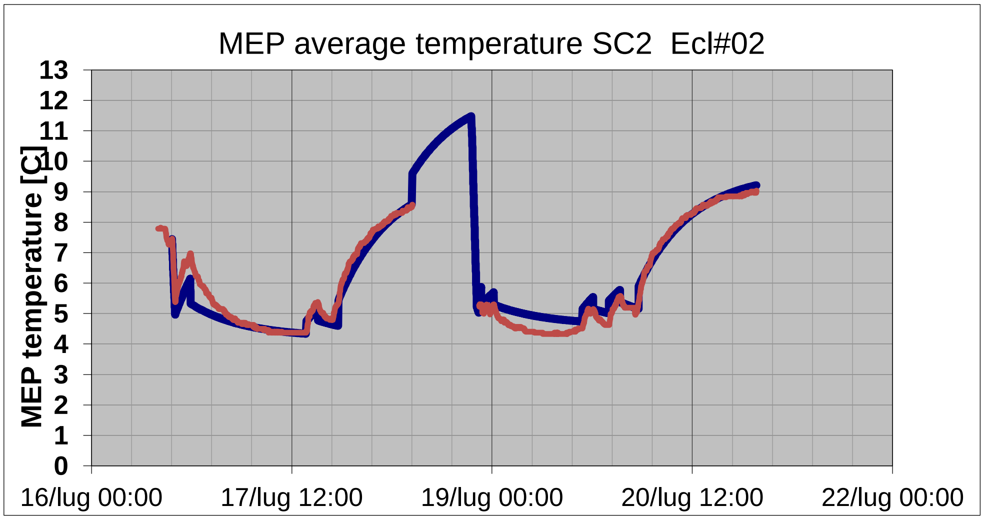


Figure 40:SC 2, Eclipse # 2, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

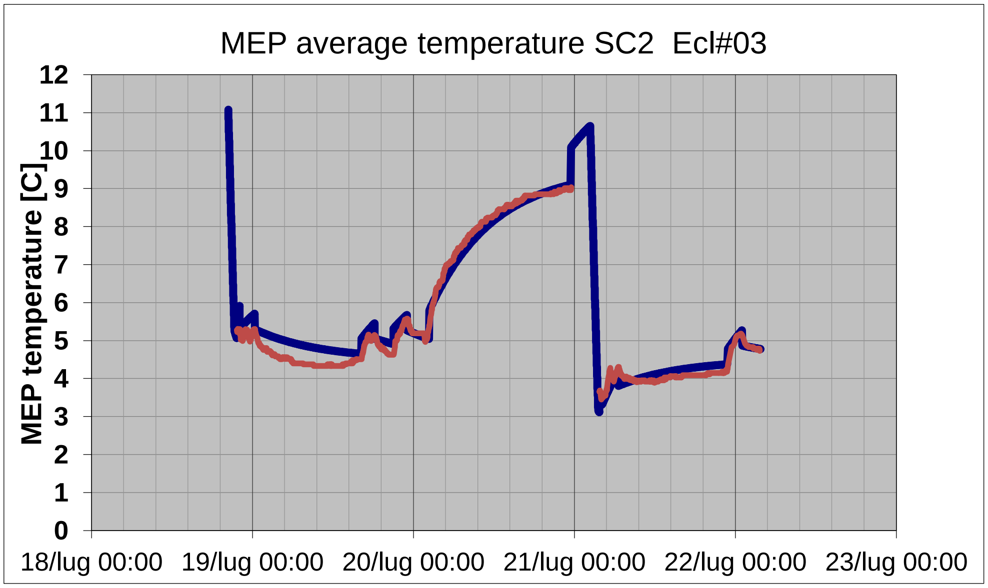


Figure 41:SC 2, Eclipse # 3, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

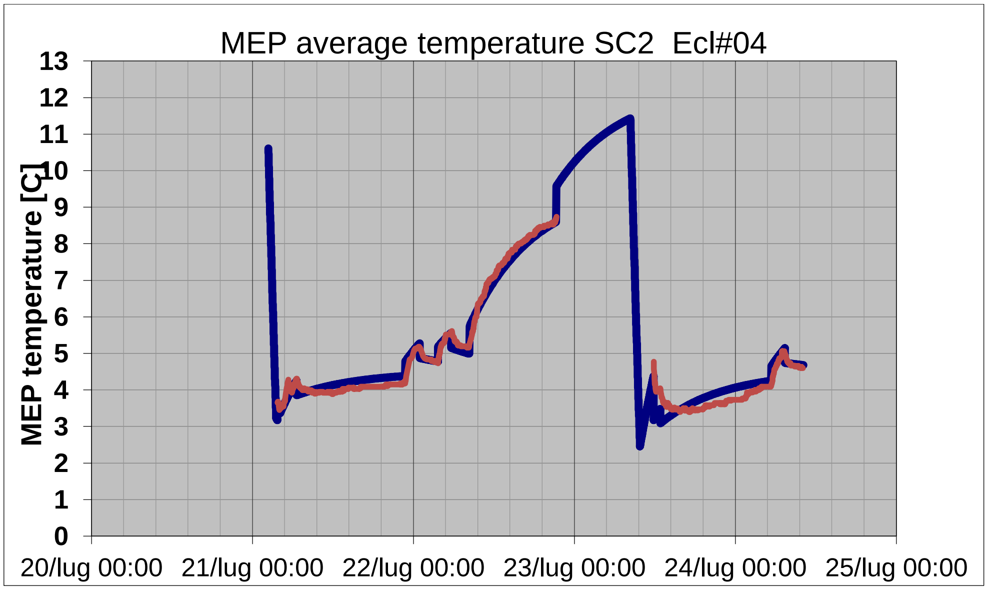


Figure 42:SC 2, Eclipse # 4, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

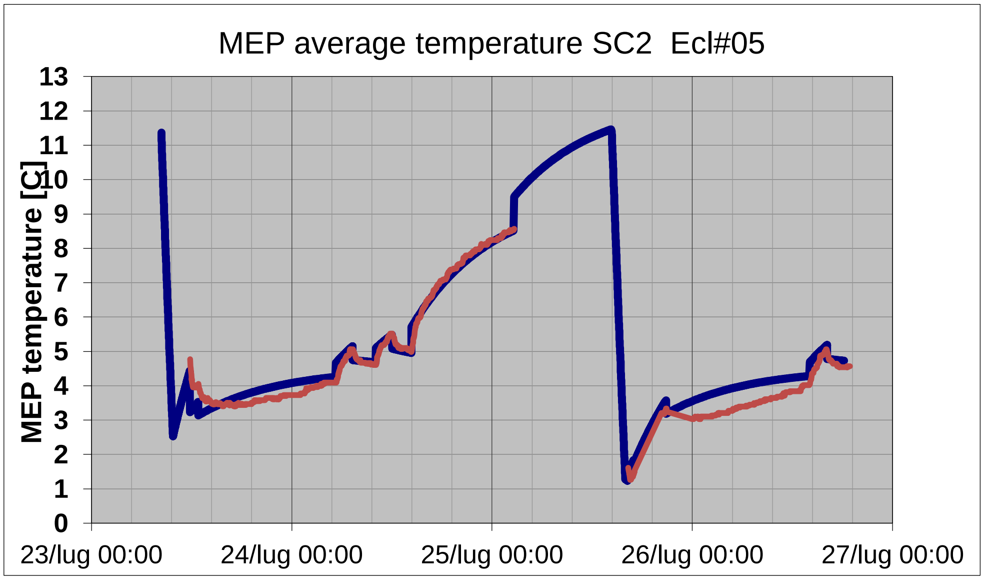


Figure 43: SC 2, Eclipse # 5, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

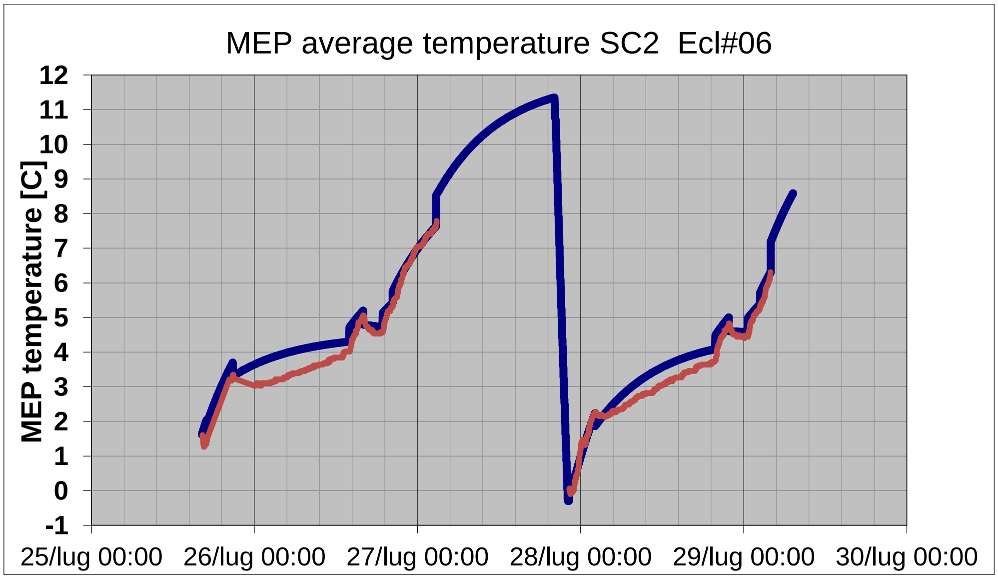


Figure 44: SC 2, Eclipse # 6, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

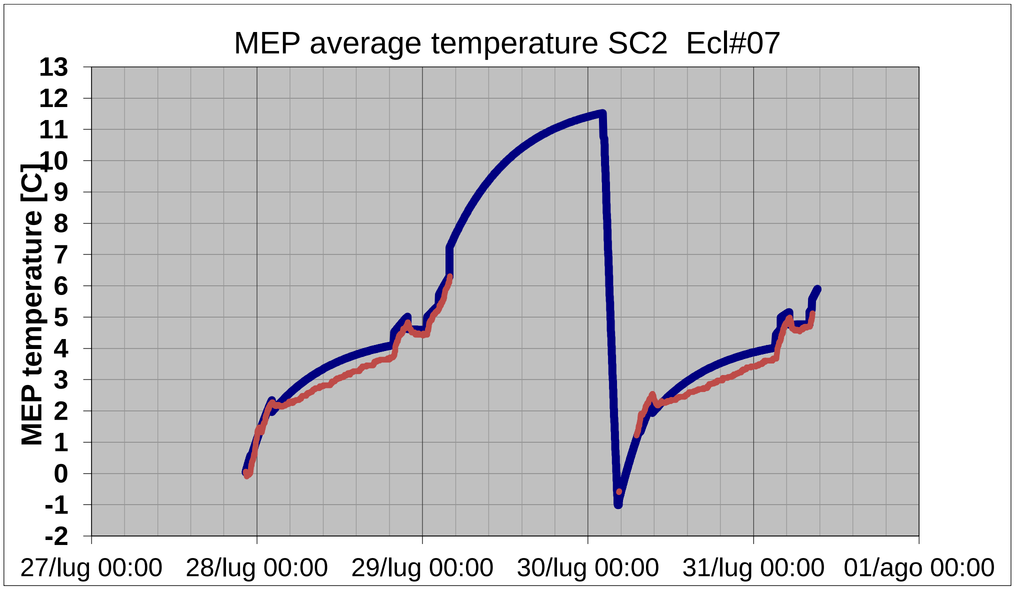


Figure 45: SC 2, Eclipse # 7, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

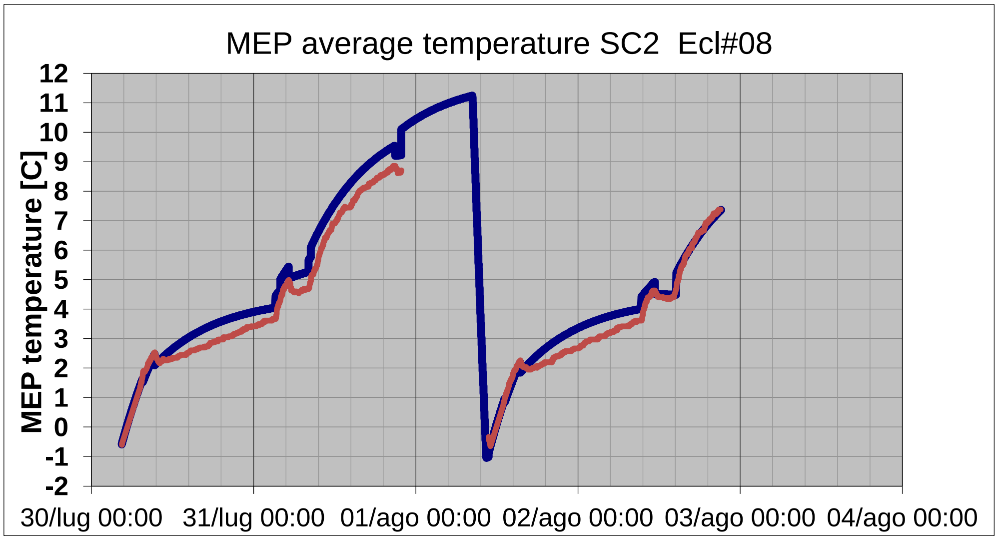


Figure 46: SC 2, Eclipse # 8, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

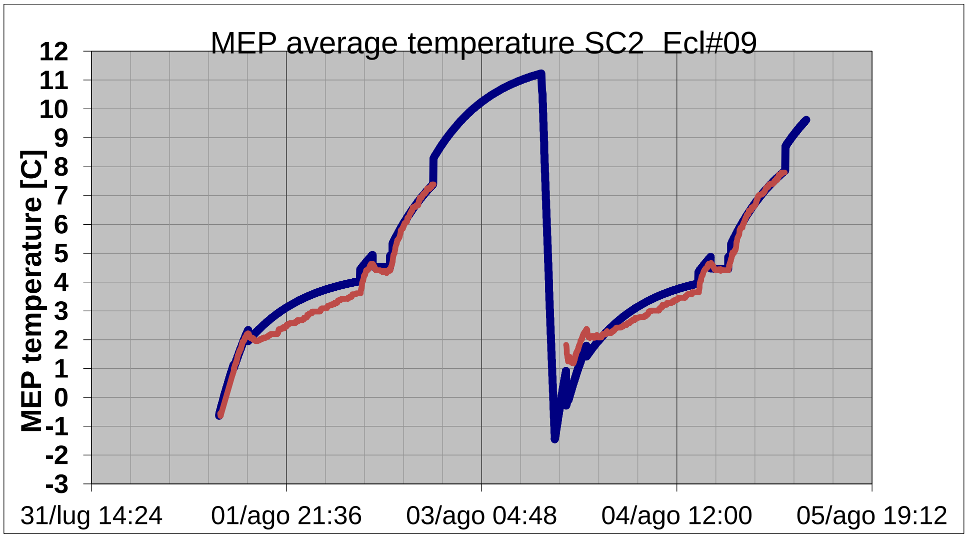


Figure 47: SC 2, Eclipse # 9, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

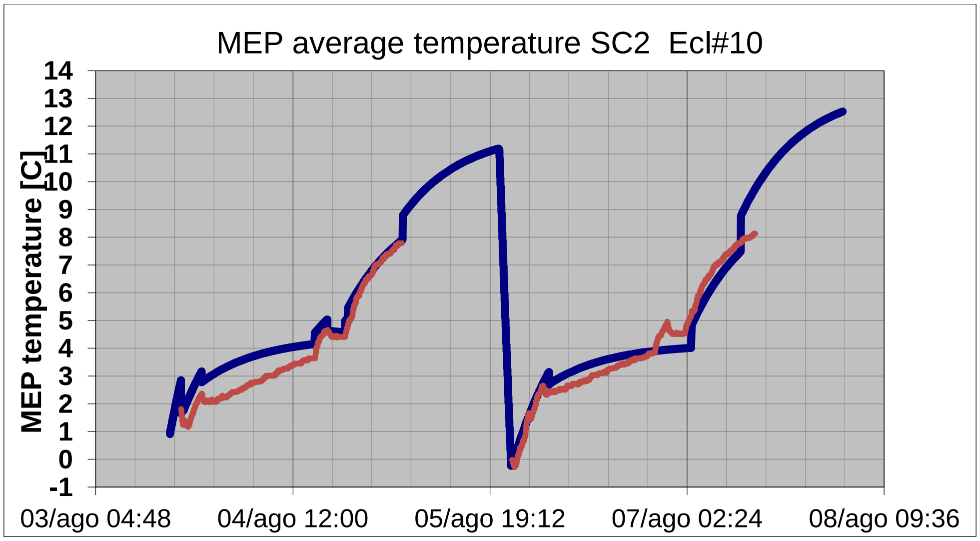


Figure 48: SC 2, Eclipse # 10, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

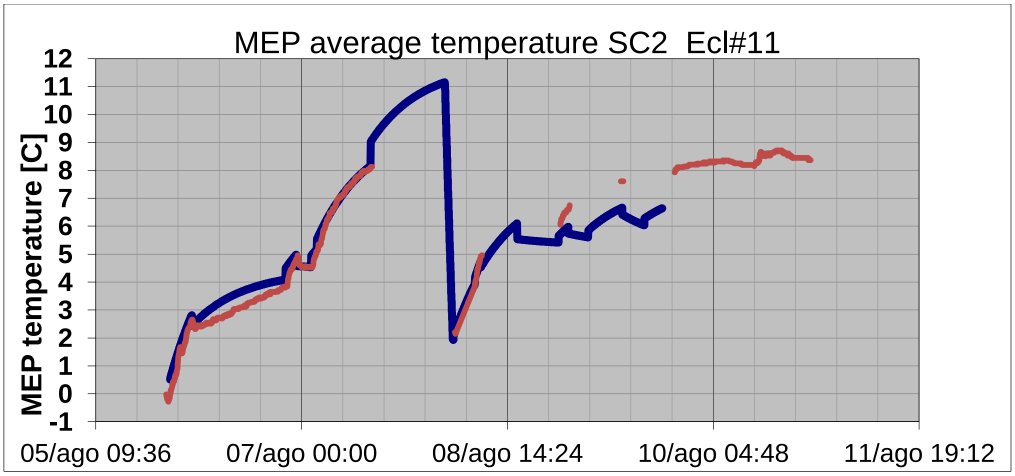


Figure 49: SC 2, Eclipse # 11, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

10.3 SC 3

Spacecraft 3 enters the eclipse season the 23rd of July, and will experience only NO BATTERY eclipses. Although there are some deviations where the telemetry is a bit lower than the one predicted from the model, the simulations seem to match quite well the data collected from the satellite. The satellite experiences eight eclipses starting the 23rd July 2012 and finishing the 10th August 2012.

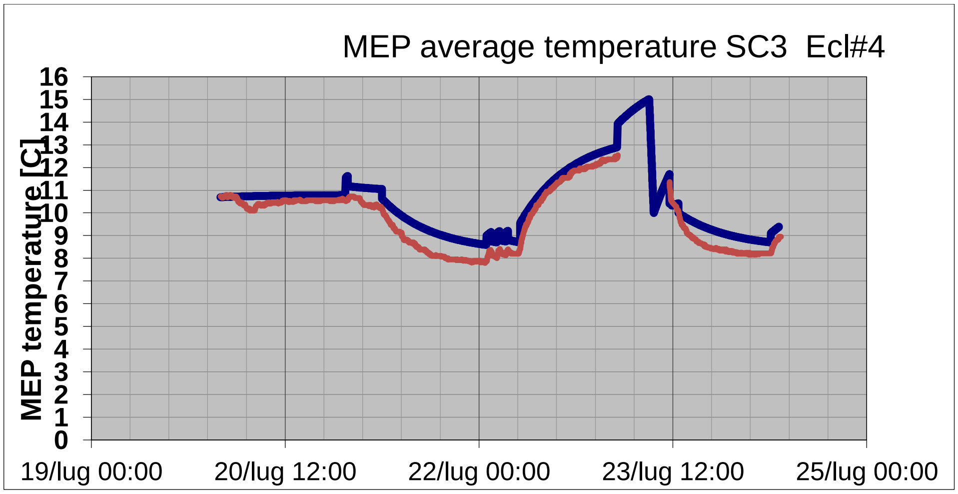


Figure 50: SC 3, Eclipse # 4, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

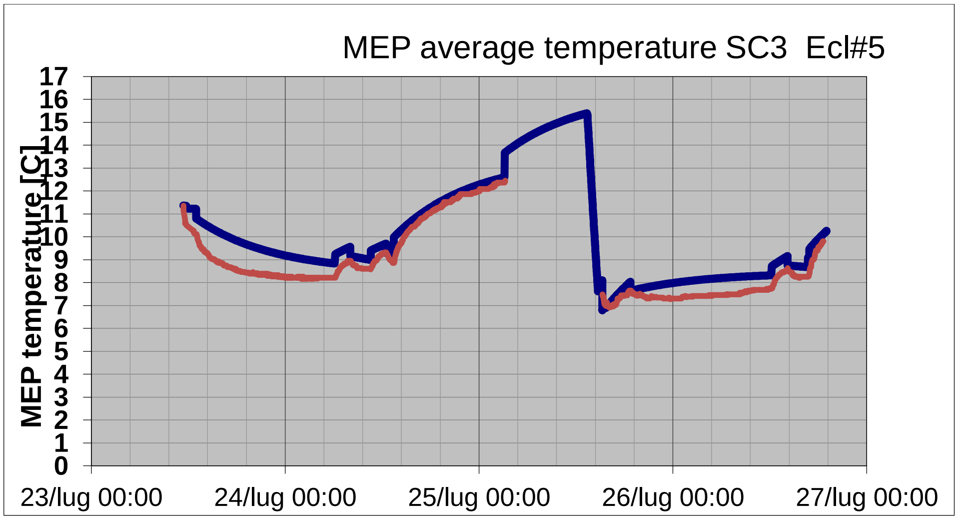


Figure 51: SC 3, Eclipse # 5, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

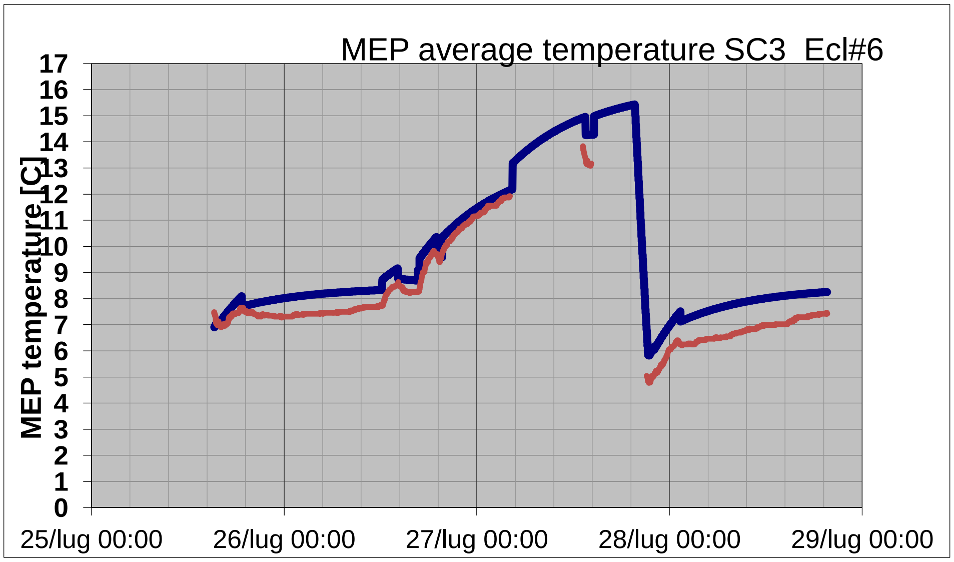


Figure 52: SC 3, Eclipse # 6, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

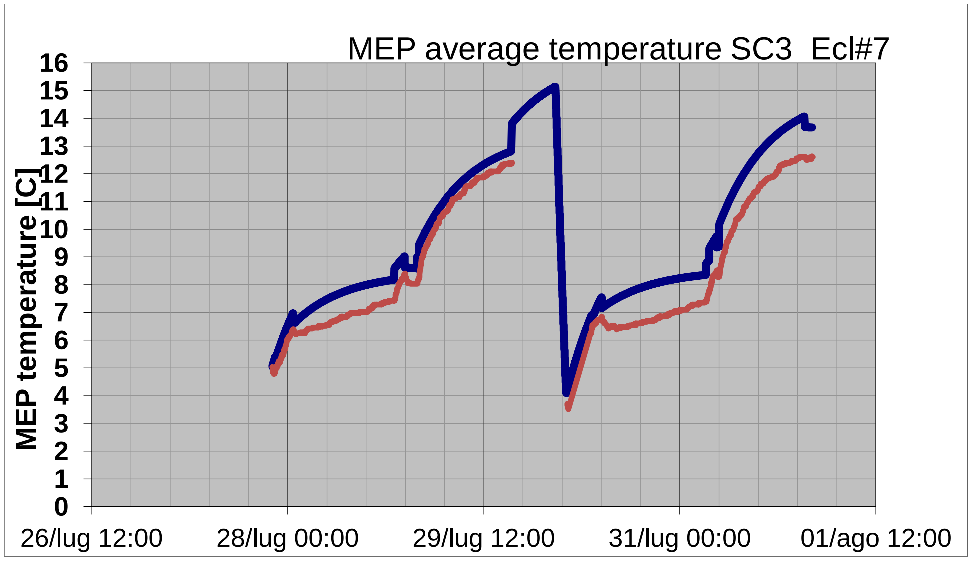


Figure 53: SC 3, Eclipse # 7, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

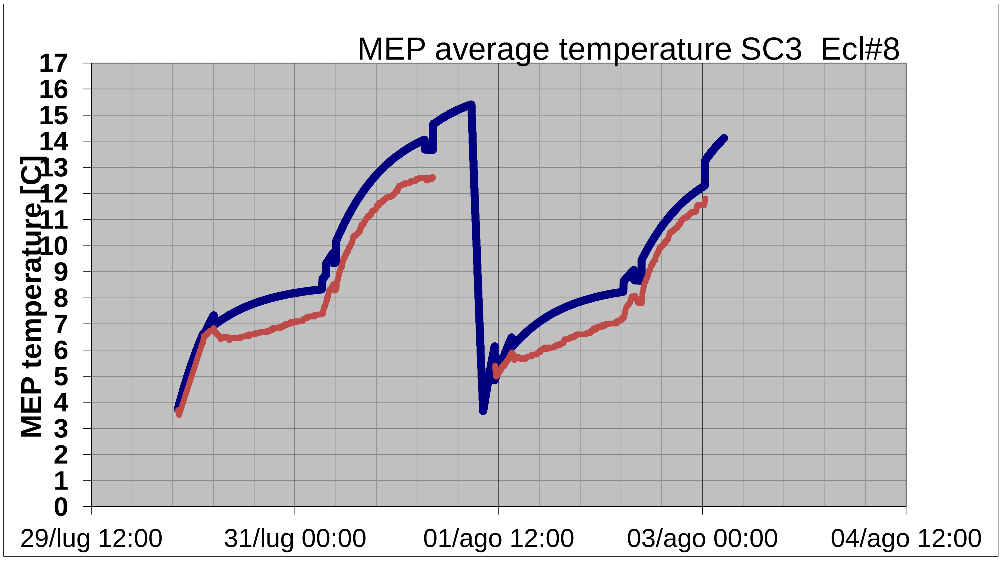


Figure 54: SC 3, Eclipse # 8, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

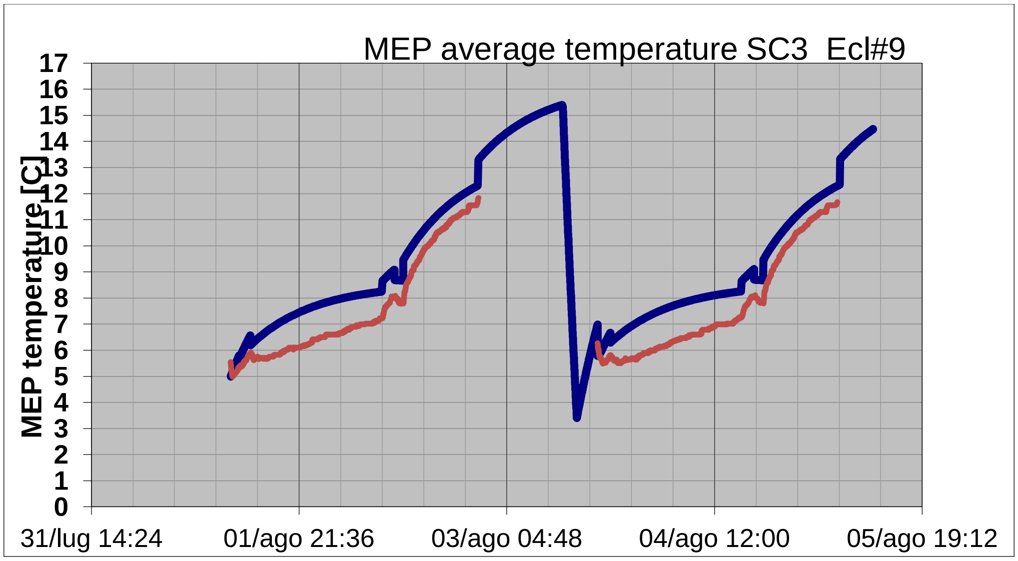


Figure 55: SC 3, Eclipse # 9, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

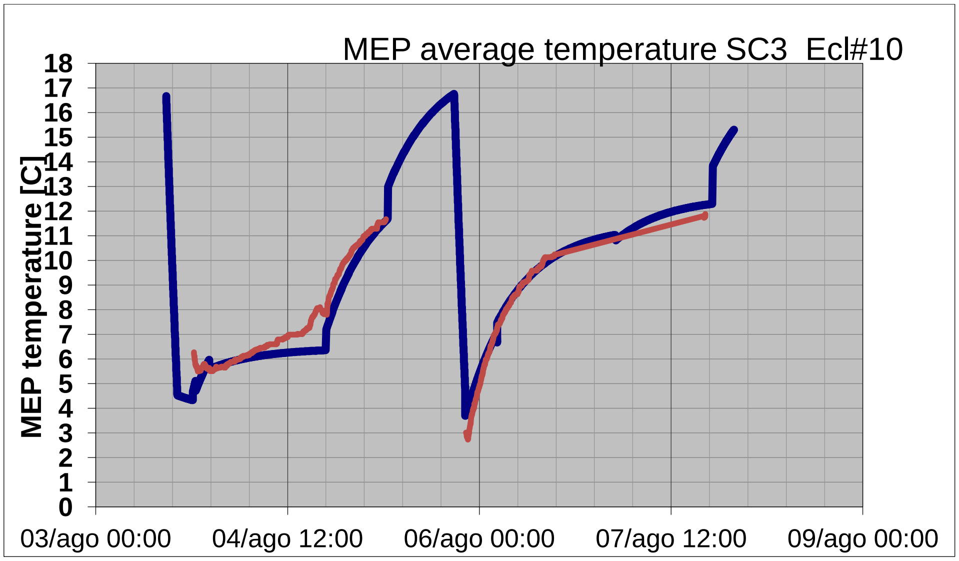


Figure 56: SC 3, Eclipse # 10, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

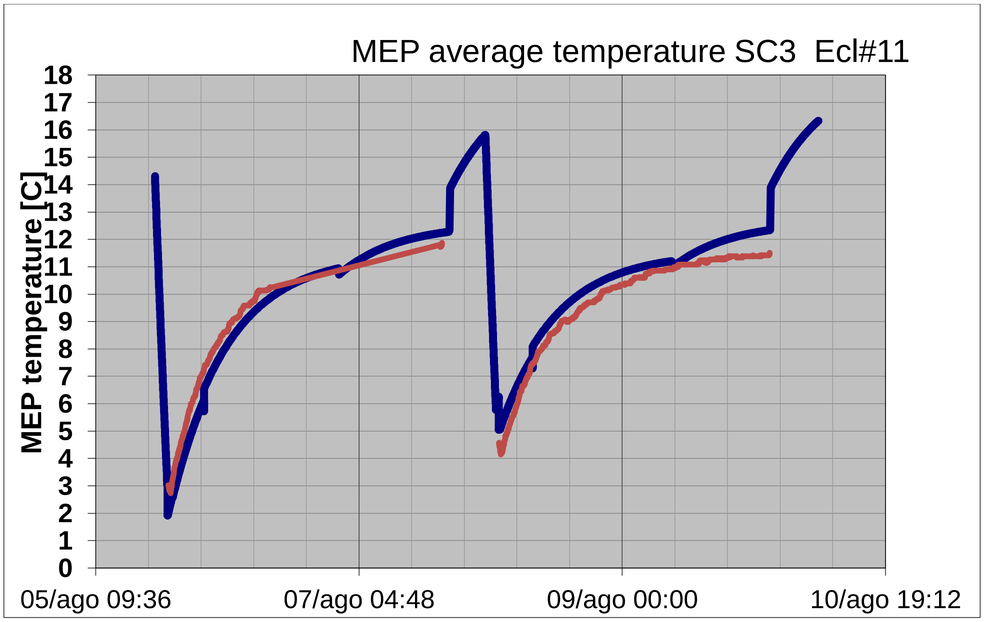


Figure 57: SC 3, Eclipse # 11, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

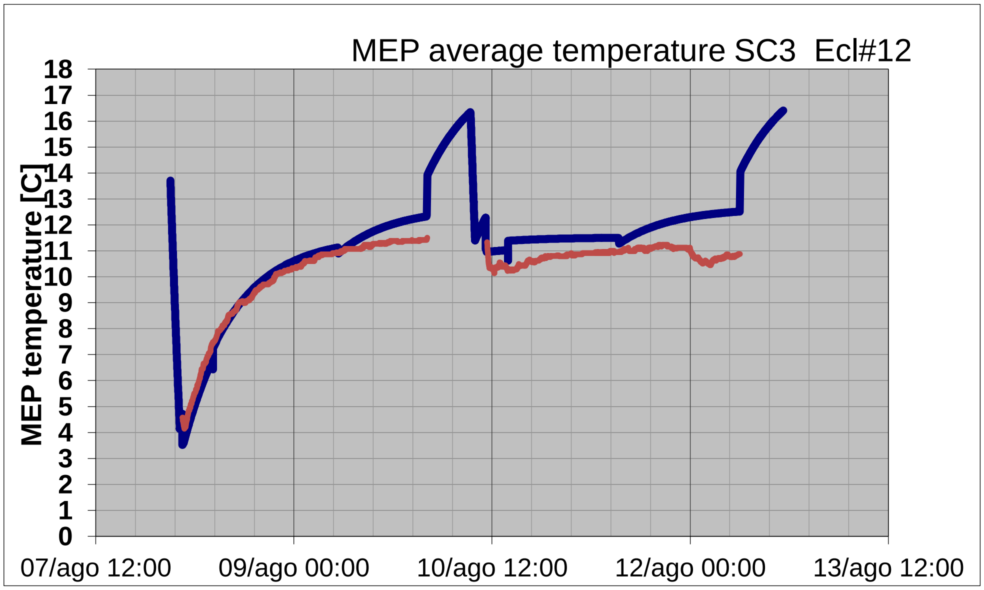


Figure 58: SC 3, Eclipse # 12, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

10.4 SC 4

Due to its characteristics (see above), this satellite is the most critical among the four CLUSTER spacecraft. The model simulates a critical temperature, that, nevertheless , is still within the acceptable range for several units. The telemetry matches quite well the predictions, which means that all the operating units didn't risk to break. The satellite experiences eight eclipses, starting the 23rd July 2012 and finishing the 08th August 2012.

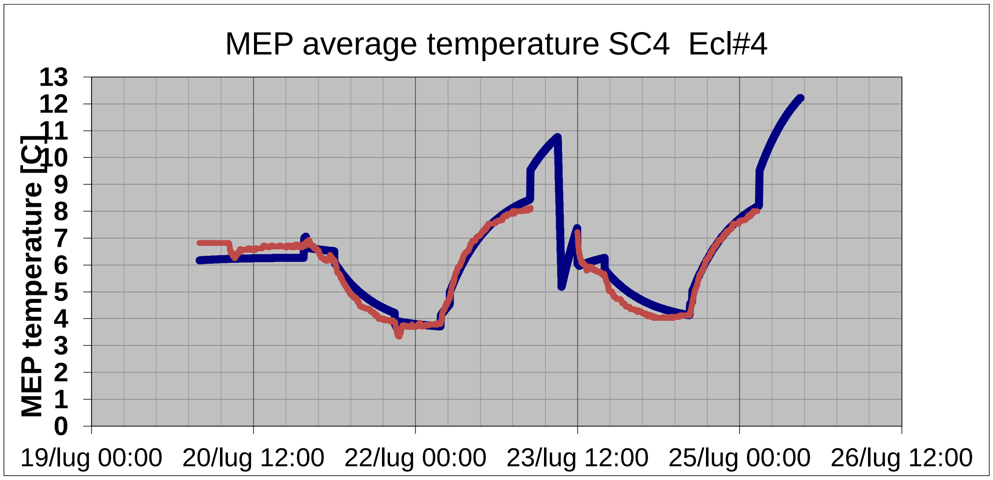


Figure 59: SC 4, Eclipse # 4, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

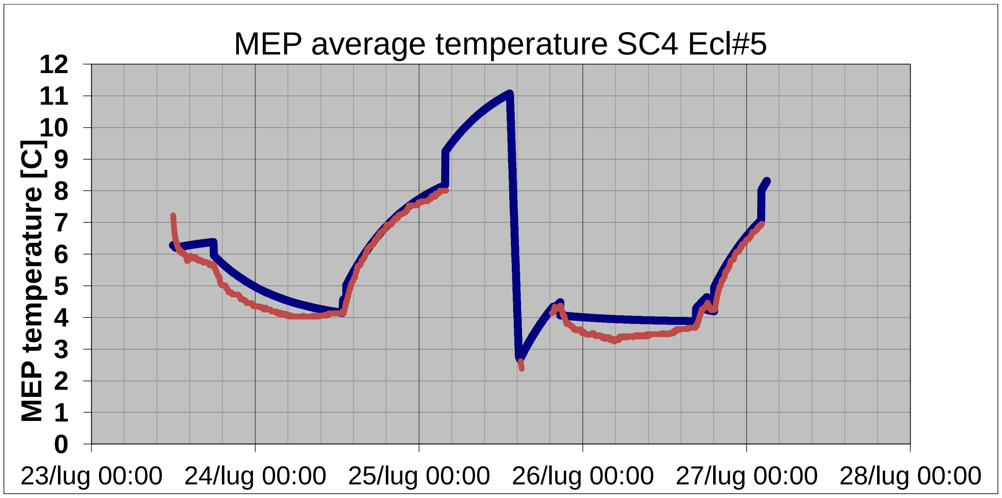


Figure 60: SC 4, Eclipse # 5, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

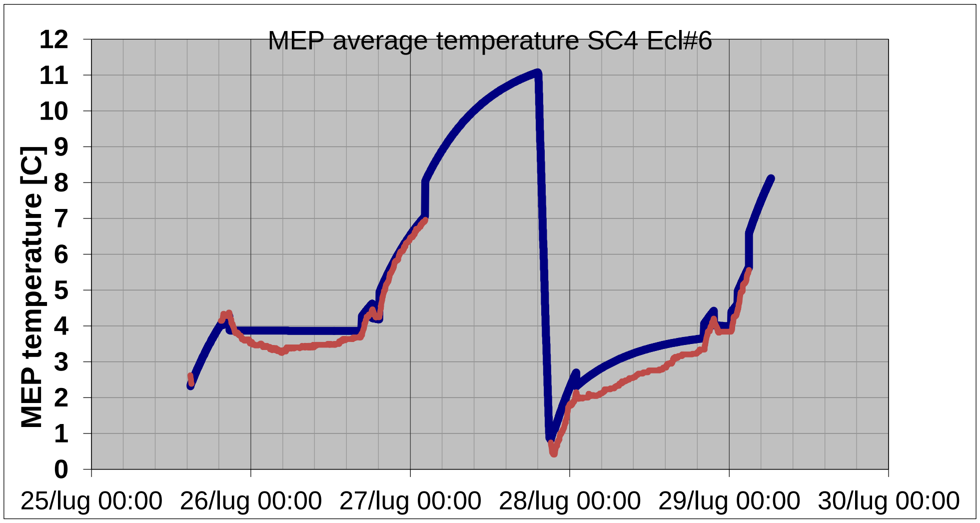


Figure 61: SC 4, Eclipse # 6, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

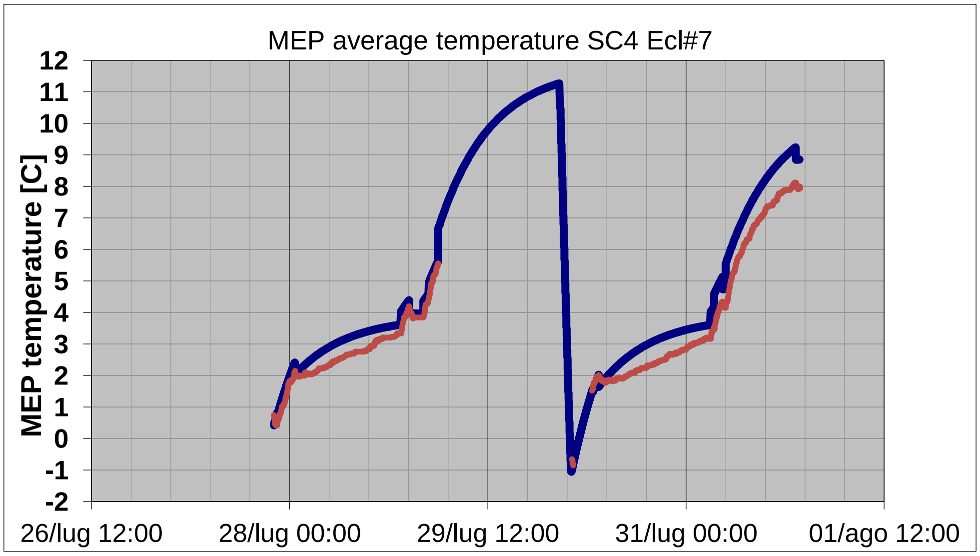


Figure 62: SC 4, Eclipse # 7, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

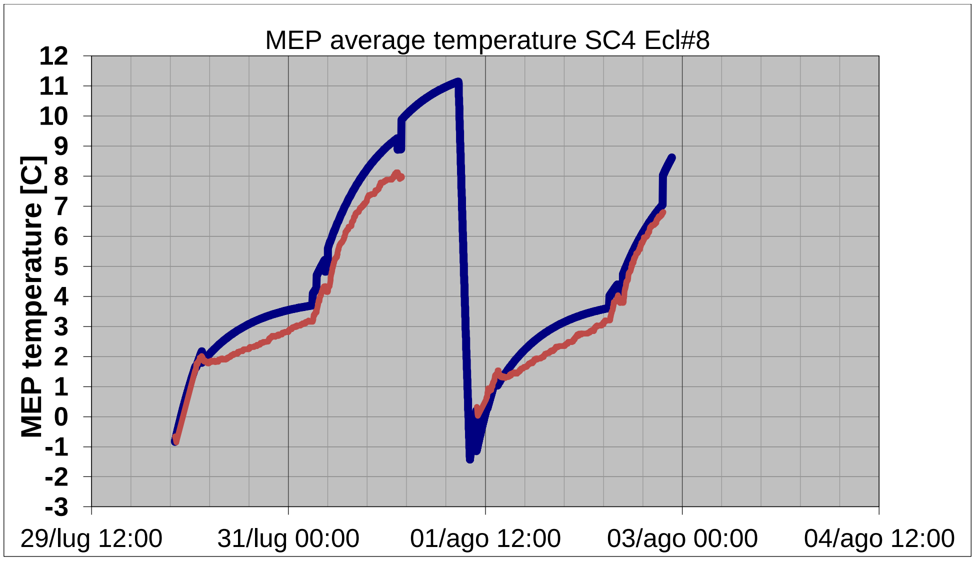


Figure 63: SC 4, Eclipse # 8, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

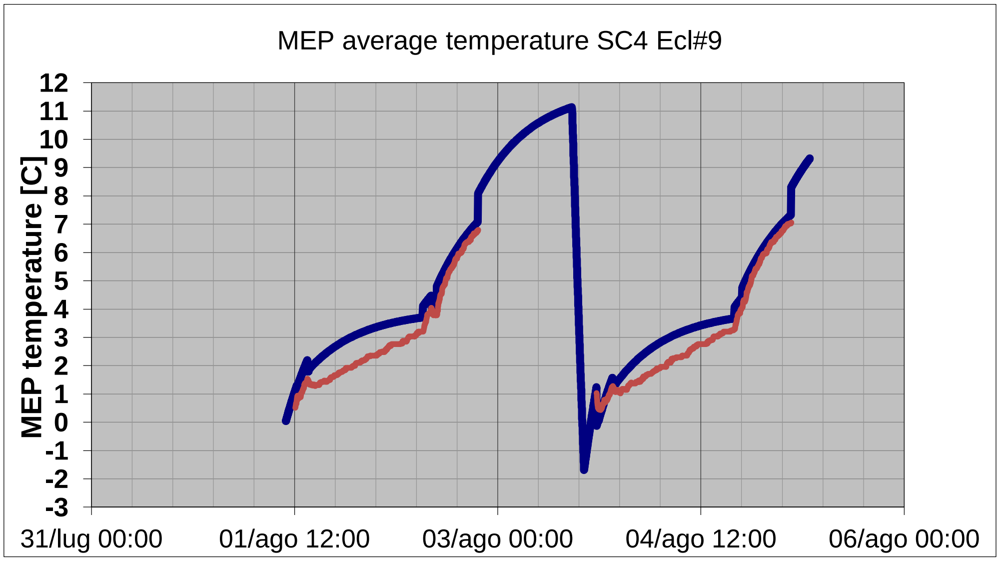


Figure 64: SC 4, Eclipse # 9, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

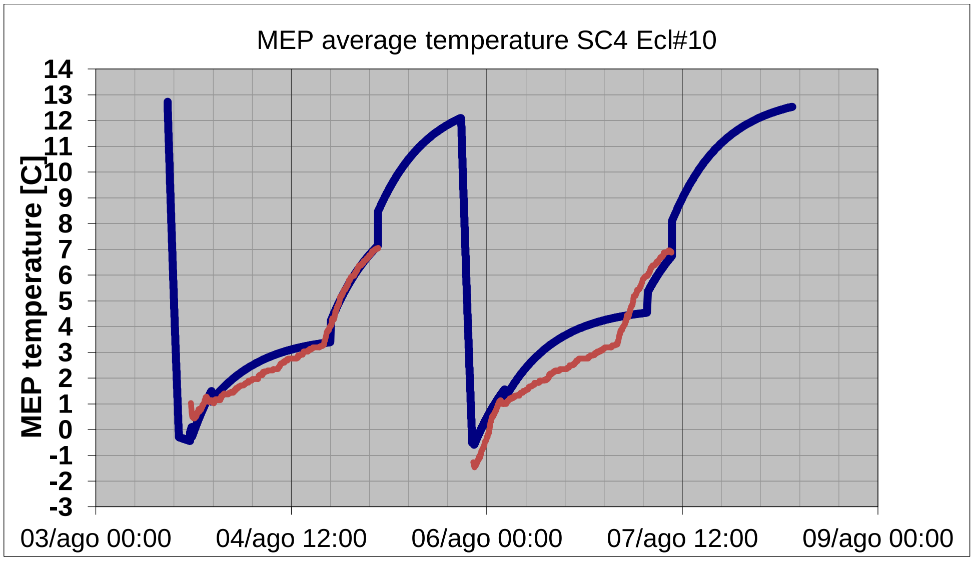


Figure 65: SC 4, Eclipse # 10, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

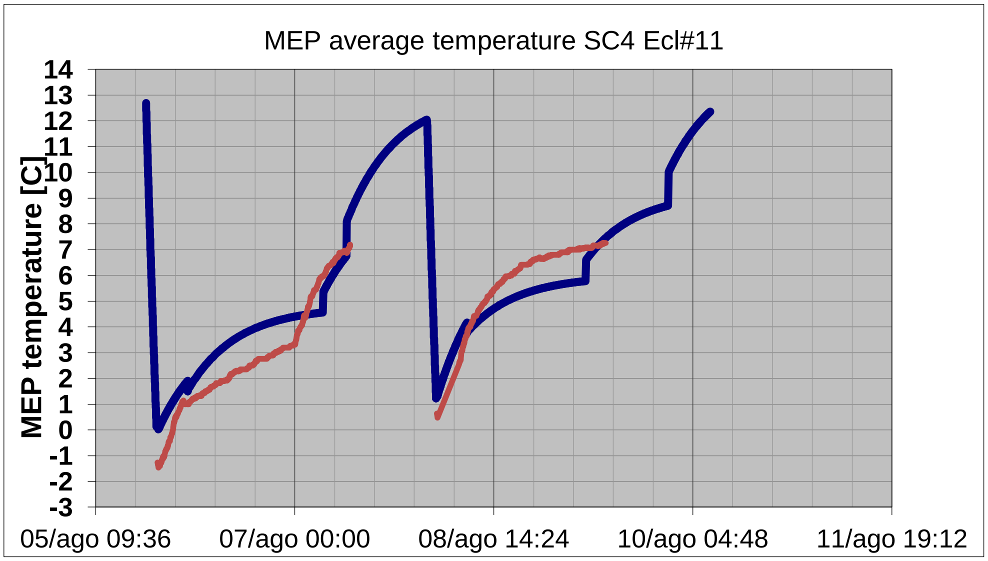


Figure 66: SC 4, Eclipse # 11, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

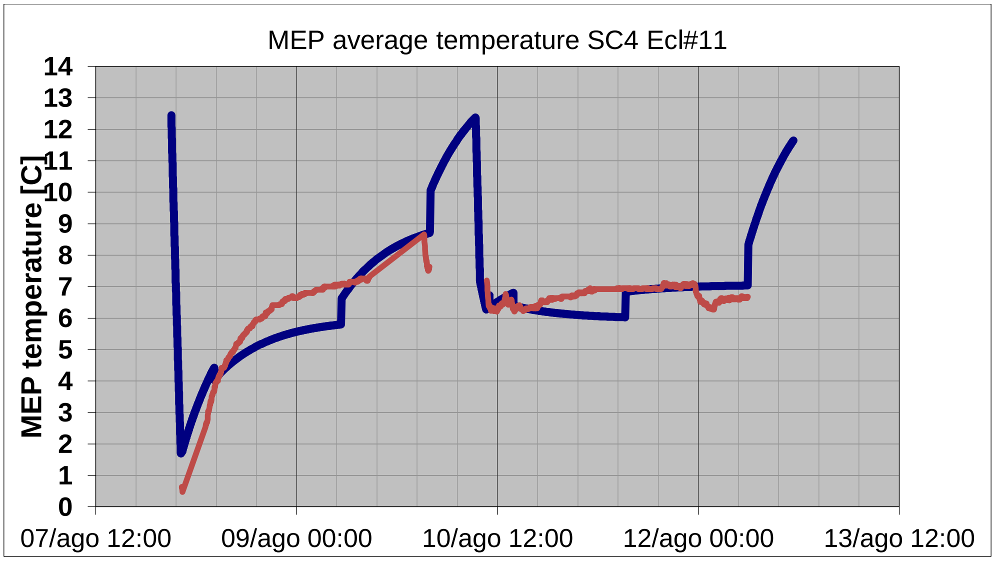


Figure 67: SC 4, Eclipse # 12, comparison between the predictions of the thermal model and the telemetry collected from the spacecraft

11. Conclusions

When launched in 2000, the four CLUSTER satellites were supposed to fly only two years. The extension of the mission brought new results, but on the other hand with the years the operating condition of the spacecraft are worsening, and in particular the Solar Array Power is decreasing and also no battery are used (especially during critical operations such as long eclipses).

This thesis work is the study of the thermal aspect of the four satellites in order to develop a thermal strategy for surviving the long eclipse season 2012.

Together with the inputs from the Flight Control Team (FCT) engineers, and tests conducted on the spacecraft, and based on a model developed in 2006 -to which some modifications have been made-, it was possible to make a thermal strategy which deals in particular with the MEP temperature and monitor critical units such as the HPA.

Despite a few deviation from the model predictions, the telemetry matches quite well the temperature given by the model. The critical temperature's threshold have not been reached, and the conditions of the satellites are according to what was expected.

Based on these results, and as such the confidence that the spacecraft can still work and get r from the outer space, a mission extension has been presented by the FCT up to 2016.

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