EntrySat Thermal Control Subsystem

(Final report)

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***Abstract*—EntrySat is a 3U-CubeSat designed by ISAE and ONERA: it's an In-Orbit demonstrator, developed to investigate the properties of orbital debris during atmospheric re-entry. Our work in this project is to improve the thermal analysis using the software Thermica, and test the thermal control algorithm for the EPS board. In particular, about Thermica part, we should validate the Structural and Thermal Model (STM), refine the Flight Model (FM) and perform a first thermal study of the re-entry phase. In this way, we can demonstrate the satisfaction of the thermal requirements and the feasibility of the mission. About the EPS board, we should verify that the thermal control algorithm works properly.**

I. CONTEXT

Orbital debris, in-Orbit collisions and satellite orbital decay represent potential threats to access to space as well as a threat to ground safety. Therefore, the EntrySat experiment consists of inserting a nano-satellite in the form of a 3U CubeSat into low-Earth orbit, similar, in principle, to secondary debris typically issued from launch vehicles or satellites. A science module operating during the re-entry phase will be able to perform in-situ measurements of the CubeSat environment (temperature, acceleration, pressure ...) as well as integrity (position, rotation speed ...) up to its destruction. Within the project, the thermal control subsystem concentrates on the prediction of the satellite's thermal behaviour during the different phases of its life. Indeed, the space environment imposes tough thermal constraints on the satellite, which could degrade or even destroy some of its components (see reference [6]).

As described in [11], the thermal control of EntrySat is quite rudimentary because the environment constraints for internal sub-systems are low (less than $-20/+60\ ^oC$). This is confirmed by the initial studies about EntrySat thermal control system. In 2013, Jean-Noël Fischer and Fleur Olagnier performed the first thermal analysis of EntrySat (reference [3]). They identified the main driving parameters and computed the first set of values needed for the thermal analysis. Their results show a tendency towards tentatively low temperatures during the orbital phase.

Then, Jessica Barbier confirmed the orbital tendency of low temperatures, incompatible with a passive thermal design for sensitive components including the batteries (reference [1]). Then, considering that the re-entry phase is the scientific core of the mission, a detailed study was performed to evaluate available time for in situ measurements of upper atmosphere environment encountered by EntrySat below 130km. Numerical results provide between 100 and 180 seconds before destruction occurs at around 100km. These encouraging computations allow for the necessary time for scientifically valuable measurements.

Considering these aspects, most of the materials and electronic components used in internal parts are compliant with the weak thermal constraints of the mission. However, the batteries are more sensitive to the temperature variations, and the manufacturer advises to keep them in the $-5/+60\ ^oC$ range for charge and discharge safe operations. To comply with the minimum temperature, two heaters are included in case it is necessary to make the environment warmer. About this aspect, the efficiency of the thermal control algorithm, which manages the functioning of these heaters, has not been tested yet.

In general, two methods are usually combined to carry out the thermal study of a satellite (see reference [10]): the first one consists of performing some tests on the satellite using a thermal vacuum chamber (TVAC) and the second one of designing a numerical thermal model of the system. These two tasks are strongly linked, because the numerical simulation aims at representing the thermal behaviour of the satellite during the tests. Last year, two students worked on the STM thermal analysis: they performed a thermal vacuum test with this model and then they created a Thermica model, in order to make a calibration of the model for the thermal analysis in orbit, as discussed in [5]. The results obtained with the thermal model's simulation were quite similar to the ones obtained with the thermal cycling test in the vacuum chamber: however, some more advanced studies could be realized to improve the model's accuracy and to obtain a better simulation (see reference [6]). After this, they created a first and basic FM Thermica model, which need to be refined and improved. This is where our work starts.

II. PROBLEM STATEMENT

About the thermal part, our work is basically using a software in order to improve the thermal analysis of the satellite. In fact, the design of the Thermal Control Subsystem and the thermal vacuum chamber test for the STM have been already done in the past years: now, we have to improve the various thermal models (STM and FM) so that we can use them for flight simulations in orbit. The software chosen in order to realise EntrySat thermal analysis is Thermica (developed by Airbus Defence and Space). The software requires some inputs to run the thermal simulation: a geometrical model, a thermal meshing, a trajectory, a kinematic file and a process diagram. In our case:

- the geometrical model are the STM and the FM, designed on the basis of EntrySat's Catia model;
- the thermal meshing is created automatically by Thermica, from the geometrical model, by associating at each geometrical object a node of the model. The meshing file also includes the list of the conductive couplings between the model's nodes, the thermal powers dissipated by the appropriate nodes and the geometry and physical properties of each of them;
- the trajectory and the kinematic file concern the simulations of the satellite's flight in orbit (only for the FM);
- the process diagram is a diagram defining the kind of calculation the software is asked to perform.

As we said before, we are supposed to continue other students' work, who were involved in this project last year, and we have to improve their models. At the beginning of our working period, we learnt how to use the software with simple examples and a *3A bureau d'étude* (BE). However, since we started working on their models, we have faced 2 main errors. The first one was about the material definition (Thermica did not identify custom materials that we added to the standard database) and the second one was about the temperature solver execution (a compiling error). Fortunately, we managed to fix these errors with the help of some Thermica experts. In fact, the biggest problem we faced during this first period, was related to the fact that there is not a great documentation about this software on the net.

Once all these errors were fixed and we were able to simulate even simple examples, we had to address the main issues of the project, which were:

- Regarding the STM, the team had already obtained some results with a real test in the TVAC (they made the temperature vary several times between -20 and 50 ^{o}C). They also had results with Thermica simulations of this STM. However, the results of the simulation did not match the ones of the tests very well. Therefore, the team wanted to validate the STM and so the first problem to solve was to modify the STM in order to have the simulation results as similar as possible to the ones of the TVAC test (see section III).
- Regarding the FM, previous members of the team had started to design it in Thermica. Nevertheless, the only modification they had done to the STM to obtain the FM, was adding the geometry of the solar panels to the model. Our work was to improve the best we could this model to represent the behaviour of the real satellite. To do that, we had to add different components (or a model of each of them), change the properties of the components, etc (see section IV).
- Regarding the re-entry phase, a member of the EntrySat team is studying it and he has obtained the heat fluxes that the satellite will receive when it is at a very low altitude (less than 200 km) thanks to a simulation with another software. The idea is to use these data in Thermica to know what will be the temperatures of all the components of the satellite during this phase. We also tried to compare these results with the results of a simulation made in Thermica with a trajectory that describes the same orbit used by the other team member. Following these steps, we could have a better idea of what will happen during the most critical phase of the mission: the re-entry phase (see section V).
- Finally, we also worked on the thermal control algorithm design and testing. It is programmed in C and it should control the batteries heaters, deciding when they have to be switched on or off, depending on the temperatures measured by the sensors (see section VI).

III. STM THERMICA MODEL VALIDATION

A. *Objective*

The first objective of our PIR was to improve the previous STM Thermica model, and to create a final model capable to produce thermal simulation results as close as possible to the real ones (which have been obtained during the TVAC test performed in June 2016, see reference [4]), so that we could use it to make a first approximation flight simulation of the satellite in orbit.

B. *Work done*

The starting point of this test is the Thermica model *Adapted STM test model* created by last year students. In order to accomplish our objective, we made modifications to this original model. In particular, the steps have been:

1) We let Thermica calculate the conductive couplings among the model's nodes: in fact, Thermica enables the automatic calculation of the conductances' values. Nonetheless, in the previous model these values were implemented in the software by hand (see reference [5]).
2) We imposed new boundary conditions. In particular, we decided to consider as boundary conditions the temperature of the TVAC walls and of the interface plate, which are controlled by the test user: about that, we made the assumption to consider the temperatures of these elements identical. So, we took the measurements taken during the test (in particular, the PT100 sensor measurements, see reference [4])) and used them as boundary conditions for the model nodes concerned. In order to do that, we created an USR file, which is a script written in a derivative of the FORTRAN code, adapted to be interpreted by Thermica: it enables to set the simulation's boundaries conditions and to implement their variations.
3) We imposed new initial conditions, using the test data given by the thermocouples. To do that, we had to make

a time synchronization between the measurements in the file which contains the measurements of the PT100 sensor, and the ones in the file which contains the thermocouples measurements. Unfortunately, we could not use the measurements of the thermocouple on the rib because the thermal contact between the thermocouple and the rib was probably bad, considering that the temperature measured was ludicrous and it should have been quite similar to the one of the longitudinal frame and of the –Z panel (see reference [5]). At this point, we made some assumptions on the initial conditions and we supposed that:

- rib temperature is equal to the mean between the longitudinal frame temperature and the –Z panel temperature;
- X panels, Y panels and +Z panel temperature is equal to the –Z panel temperature because the conductivity is high;
- transversal frames and rods temperature is equal to the longitudinal frame temperature;
- all the boards are at the same temperature;

In Figure 1, you can see what are the components interested in these assumptions.

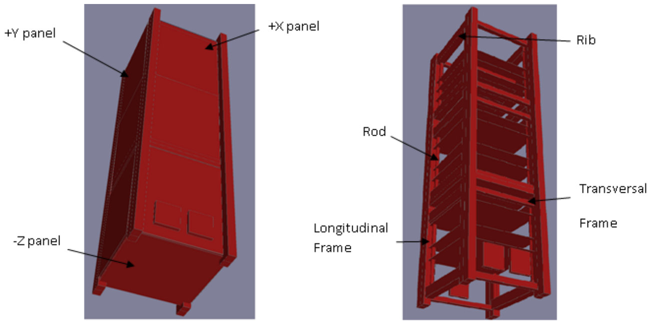


Fig. 1. STM components

In any case, this step is not so fundamental because we want essentially to analyse the regime behaviour of the model, and the initial conditions don't influence it.

4) We changed the specific heat value of the board material for the batteries. In fact, during the TVAC test, the thermocouple was not stuck on the batteries, but on the board on which they were set up (so, the test operators didn't measure exactly the temperature of the batteries, see reference [4]). But, in the Thermica model, the node of the batteries represents the batteries themselves (and so we measure the temperature of the batteries), and the simulation fell the effect of this discrepancy.
5) We deleted the dissipations present in the model. In fact, we noticed that, during the simulations in Thermica, the temperature of the nodes examined reached an higher value during the cycle that was quite similar to the real one: we can't say the same about the lower temperature, which was higher than the real one. So we thought that this problem was linked to the presence of 3 dissipations elements (0.34 W each) on the main board, on the UHF/VHF board and on the magnetorquer board: in fact, after deleting them, the simulations were way better and the results were more similar to the real ones.
6) We changed the density of the boards' materials. In fact, in the previous version, all the boards had the same dimensions (area and thickness) and the same density, so they had all the same mass: but, in the reality, they haven't the same mass. So, in order to consider this issue (also considering that the mass influences the specific heat and so the results of our simulation), we defined a specific density for each board, so that the mass of each one of them is equal to the mass inserted in the mass budget in the FYS proposal (see reference [11]).
7) We added the batteries, represented as parallelepipeds on the batteries board. After this step, we put again the value of the board material specific heat for the batteries board equal to the others (see step 4), but we put on the batteries board itself the batteries (considered to be made in aluminium as they were during the TVAC test with the STM, see reference [4]) with an high specific heat.

After step 3, we created 5 different models and made simulations with each one of them. In particular, you can see the features of each model in Table I.

Model	Features
1	• Automatic Thermica conductive couplings; • New boundary conditions; • New initial conditions;
2	• Automatic Thermica conductive couplings; • New boundary conditions; • New initial conditions; • New specific heat value for the battery board
3	• Automatic Thermica conductive couplings; • New boundary conditions; • New initial conditions; • New specific heat value for the battery board • No dissipations
4	• Automatic Thermica conductive couplings; • New boundary conditions; • New initial conditions; • New specific heat value for the battery board • No dissipations • New density value for all the boards
5	• Automatic Thermica conductive couplings; • New boundary conditions; • New initial conditions; • New specific heat value for the battery board • No dissipations • New density value for all the boards • Parallelepipeds batteries inserted

TABLE I
STM MODELS FEATURES

For more details, see reference [9].

C. *Results*

The output of the simulation that we have used in this test are some .xls files created by Thermica which contain, for each node of the model, the temperature varying with time during the simulation.

For each model created, we have analysed the temperature of the nodes related to the batteries, the UHF/VHF board, the -Z panel, a high rail and a part of the longitudinal frame, because these are the nearest nodes to the positions where the thermocouples were stuck during the TVAC test (see reference [4]). In particular, we compared the temperature of each one of these nodes with the temperature measured by the respective thermocouple, we made graphs representing the 2 data series (Thermica data and experimental data, see Appendix A) and we calculated the deviations between the 2 data series themselves.

For analysing the deviation, we have used the following formula:

$$J = \sum_{t=0}^{t_{end}} \sum_{i=113,124,535,8120,32100} \frac{(T_i^{experimental}(t) - T_i^{Thermica}(t))^2}{\sigma_{T_i}^2}$$

where:

- $113, 124, 535, 8120, 32100$ are the numbers of the nodes in which we are interested;
- σ_{T_i} is equal to $1\ ^{o}C$ (assumed temperature error).

D. Conclusion

As you can see from the tables A.1, A.2, A.3, A.4 and A.5 in the Appendix A, mathematically speaking, the model which globally gives the best results is the 3^{rd} model (see Section A.3 in Appendix A). In particular, for each node and for each model, we put here in Table II the list of the J values calculated, writing in **bold** the best results (i.e. the smallest ones).

Node	1st model	2nd model	3rd model	4th model	5th model
Battery 4.1 [113]	583458,907	165110,211	**54045,8993**	91922,9677	80117,4207
UHF board [124]	431618,168	441028,479	12715,44	12374,6863	**6371,15667**
-Z frame [535]	**16496,8218**	18047,5854	52081,3286	70025,8052	65216,3444
Rail haut (2) [8120]	191299,4908	242964,883	152806,883	**140289,245**	245960,901
Longitudinal frame 5 [32100]	**74177,4113**	92326,2133	123163,648	129593,506	165157,653
TOTAL	1297050,799	959477,3717	**394813,199**	444206,2101	562823,4752

TABLE II
J VALUES FOR EACH MODEL AND NODE

So, the best model is the 3^{rd} one, which is the model that we are going to use from this point forward for all the simulations with the STM: in fact, it is the model which makes the best approximation of the batteries temperature (which is the most critical because the batteries are the most sensitive components). For this reason, we made with this model a longer simulation, which you can observe in section A.6 in Appendix A. Probably, the models 4 and 5 give worse results about the batteries board because, varying the value of the boards' mass (and so varying the specific heat of each board) and adding batteries with an high specific heat, make the thermal inertia of the batteries board bigger: obviously, this cause an offset between the experimental curves and the simulations' curves, and this offset makes the deviation values bigger. Considering the starting model, we can say for sure that the model is improved and that we could use it to make a first approximation flight simulation of the satellite in orbit. In Figure 2, you can find the approximations of each model for the batteries temperature (model 3 and experimental data curves are thicker than the others).

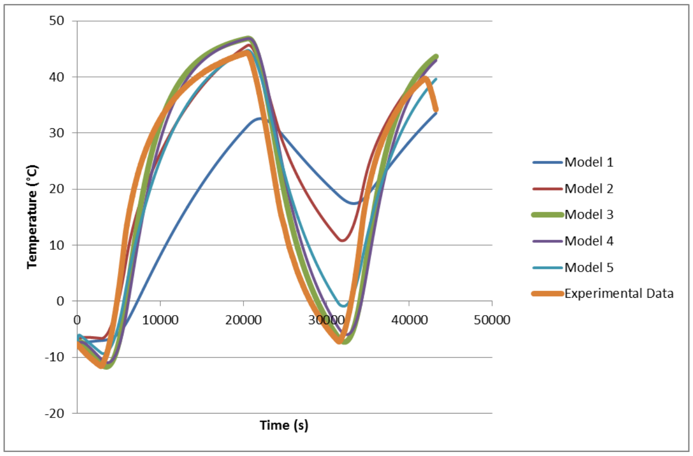


Fig. 2. Batteries temperature approximations for each model

IV. FM REFINEMENT

A. Objective

The second objective was to improve the Flight Model that was started by previous members of the team with Thermica, in order to represent all the components of the satellite as close as possible to their reality.

B. Work done

When we started working on the project, the only change that was added to the FM (with respect to the STM) was the addition of the solar panels to the geometry of the satellite. In order to accomplish our objective, we made modifications to the original model. In particular, the steps have been:

1) As made before, we let Thermica calculate the conductive couplings among the model's nodes: in fact, Thermica enables the automatic calculation of the conductance's values. Nonetheless, in the STM model these values were introduced into the software by hand (see reference [5]), and for the FM, there was not neither the manual nor the automatic calculation of them, so the software was taking into account radiation as the only way to exchange heat.
2) We calculated the properties of the solar panels. In the model, we represented a solar panel as it had only one layer, but in fact, it had three layers. We had to specify to the software, the material of which the solar panels were composed (density, conductivity, specific heat, emissivity, absorptivity), even if it is actually the addition of layers of different materials. Therefore, we had to define an equivalent material and introduce the values calculated in the software. We knew the properties of the materials that composed a solar panel and the layout of them to form each solar panel (one layer of: cover glass, electronic equipment and an adhesive layer in series, and four connectors in parallel): so, we calculated the values of the equivalent material, created a new material in Thermica with these values (the radiative properties are considered equivalent to the ones of the

external layer), and added it to the material database (see Table III, where in **bold** we have reported the final used values).

	Cover Glass	Electronic equipment	Adhesive layer	Connectors	Total	Total SI units
Thickness (mm)	0,1	0,15	0,5	0,025	0,775	**0,0008**
Area (cm^2)	30,81	30,81	30,81	0,5		
Volume (cm3)	0,3081	0,46215	1,5405	0,05	2,361	
Density (g/cm^3)	2,6	5,323	1,05	8,359		
Mass (g)	0,8011	2,4600245	1,617525	0,41795	5,297	0,0053
Total density (g/cm^3)					**2,244**	
Total capacitance (J/K)					2,809	
Total specific heat (J/K/kg)					**530,344**	
Total conductance (W/K)					7,220	
Total conductivity (W/K/m)					**9316,129**	

TABLE III
SOLAR PANEL EQUIVALENT MATERIAL CALCULATION

3) We needed to add the power dissipation of each board of the FM. We started with the dissipations added (with resistors) to the STM for the TVAC tests, but we concluded that this was not enough and we saw in reference [11], a table with the power consumption of each board for the orbital mode.

Board name	GPS	Iridium	EPS	OBC	IMU	VHF	MTQ (Idle)	Sensor Board
Average power consumed (mW)	113	8	263	375	39	525	213	8

TABLE IV
SYNTHESIS OF POWER CONSUMPTION IN ORBITAL MODE

We made the hypothesis that the efficiency of each board is very low, and that the power consumed is equal to the power dissipated. We added these values in Thermica. Unfortunately, we have not found any way to make these dissipations vary over time; we thought that, maybe, with a USR file it was possible but in the Thermica Support manual it is explained that you can impose (with an USR user file) variables like solar flux, but it does not say anything about power dissipations.

4) Regarding the material of the boards, at the beginning, we did not change its thermal properties but we changed the density of each board according to the mass and volume of each board, specified in reference [11] (the cross-area of the boards was calculated measuring one board of the model in Thermica). Therefore, for the density calculation, we have taken into account not only the boards, but also the components that were on the boards (such as the Iridium modem); obviously, this was not perfect, as the things that were on the boards did not have the same thermal properties as the boards themselves. Later on, we discovered which was the material of the boards (FR-4 epoxy), and we introduced its thermal properties in the software.
5) We supposed that the different components of the boards, such as the Iridium modem (with the shape of a volumic box), could have an influence on the view factors for radiation computations (we can find their dimensions with the CAD file of the satellite, but not the thermal properties). However, before making the great effort of adding all the peculiar shapes that exist on the boards, we decided to add the approximate shape of the batteries (4 cylinders) to see if we saw any significant changes. The problem with this, is that the contact surface would be very little whereas in the real satellite there is some glue to stick the batteries. Our first attempt to solve this is to put the cylinders some millimetres below the batteries board so the contact surface can be higher.
6) We thought that probably the PC104 connectors, that link most of the boards, could have an influence on the temperatures of the boards, so we decided to add them to the model. We started with a simple approach, saying that as there are four rows of connectors inside a plastic box, we could calculate the properties of an equivalent material that represents the behaviour of 5 rows of plastic and, between them, a row of the connector material (so 4 rows for the connector in total). We can see it in Figure 3.

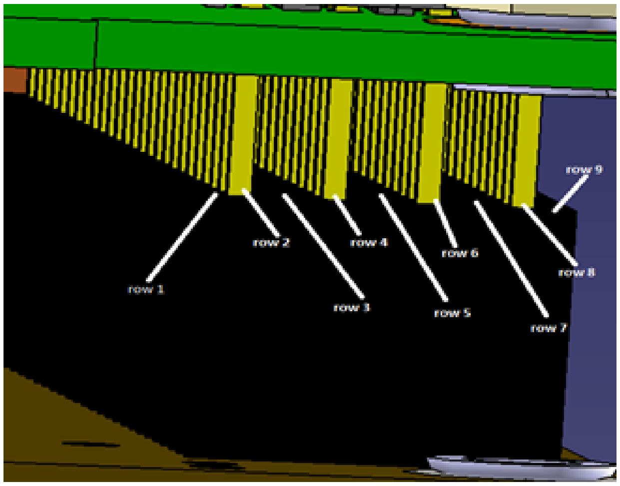


Fig. 3. CAD file with zoom on some PC104 connectors and with some parts hidden

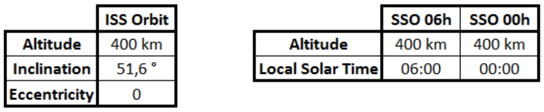
We have nine rows in total, and the important heat flux would go from one board to another so the rows are in parallel and not in series. We searched the materials for the plastic and the connectors, their thermal properties, and the geometrical dimensions obtained from the CAD file. We represented them as volumic boxes with the properties of the equivalent material, calculated as the equivalent of nine rows in parallel for the mentioned materials, with the radiation properties of the plastic, that is the material of the exterior layer.

It should be mentioned that there is a doubt about the direction of the cylinders of the batteries. We have put them as they are in the CAD file but in other image, they are rotated 90^o. In addition, we discovered later that there was another connector missing for the batteries board. With this new information, we made different model.

For more details, see reference [8].

C. Results

For the simulations, we considered three different orbits during four revolutions (see table V): one of them similar to the ISS orbit (this cubesat could be launched from there), and sun-synchronous orbits with cold case and hot case: local solar time 00:00 and 06:00 respectively (this last two orbits are characteristic of the VEGA launcher).



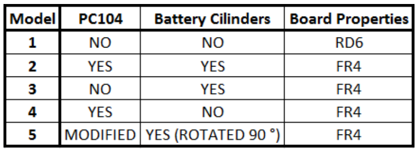
	ISS Orbit
Altitude	400 km
Inclination	51,6 °
Eccentricity	0

	SSO 06h	SSO 00h
Altitude	400 km	400 km
Local Solar Time	06:00	00:00

TABLE V
PARAMETERS OF THE THREE ORBITS

The idea is to have, for each orbit, these different models (see table VI):

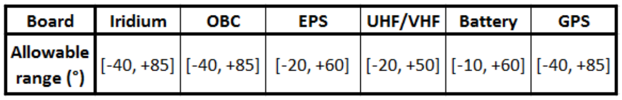
- Model 1: Without PC104, with board densities according to the beginning of step four, and without batteries cylinders.
- Model 2: With PC104 (simple model) and with boards of FR4 and with batteries cylinders.
- Model 3: Without PC104 (simple model) and with boards of FR4 and with batteries cylinders.
- Model 4: With PC104 (simple model) and with boards of FR4 and without batteries cylinders.
- Model 5: like model 2 but with PC104 in batteries board and cylinders rotated 90^o.



Model	PC104	Battery Cilinders	Board Properties
1	NO	NO	RD6
2	YES	YES	FR4
3	NO	YES	FR4
4	YES	NO	FR4
5	MODIFIED	YES (ROTATED 90 °)	FR4

TABLE VI
SUMMARY OF THE DIFFERENT MODELS

According to the datasheets of each component, the allowable temperature range for each one is:



Board	Iridium	OBC	EPS	UHF/VHF	Battery	GPS
Allowable range (°)	[-40, +85]	[-40, +85]	[-20, +60]	[-20, +50]	[-10, +60]	[-40, +85]

TABLE VII
ALLOWABLE TEMPERATURE RANGE

The outputs of the simulation are the .xls files that contain, for each node of the model, the temperature varying with time. With these data, we have plotted the results for the nodes we considered significant.

Considering that the temperatures of the GPS and batteries boards are also important, we made a plot only for them. The computation time for these simulations is 2 minutes approximately.

For each model created, we analysed 4 periods of an orbit, just in case the initial temperatures were not good and some strange behaviour appeared (with only one revolution, we may not see this trend). Indeed, we saw that a trend exists and within four orbits, it has been more or less stabilized.

D. Conclusions

As you can see from the tables in the Appendix B, the batteries, which are the most critical component, stay always in the allowed range [-10, 60] although the help of heaters could be needed just in case (at some points its temperature is close to -10). With the sun-synchronous local solar time 06:00 the boards may reach high temperatures, especially when the end of the mission, and therefore the re-entry phase, begins because the altitude will be lower. For this reason, considering that in this orbit the thermal control would be very difficult, we think that it would be better to consider another orbit for the mission. Adding the PC104 connectors and the cylinders makes the temperature variations lower, because most of the components of the satellite are now linked, and that makes the temperature more homogeneous: the resistance to thermal variations is higher.

As we can say that taking into account the PC104 and the batteries make significant changes, we conclude that we should take for the moment model 2 or 5, which include everything. They present very similar results (see plots for GPS and batteries temperatures in Appendix B) except for the orbit SSO 06h because, the fact that the batteries board also has a connector (model 5), lowers the temperature as we explained in the previous paragraph.

V. THERMICA RE-ENTRY MODEL TEST

A. Objective

Our third objective was to perform a thermal analysis on the FM Thermica model during the re-entry phase, in order to find out the altitude at which the satellite will be destroyed by the atmospheric friction.

B. Work done

The starting point of this test is the FM Thermica model. In order to accomplish our objective, we realized 3 new different models: the difference between the first 2 is only about the boundary conditions imposed; the third one is an in-orbit simulation at a fixed altitude. The steps followed have been:

1) We imposed new boundary conditions in order to obtain the first model. In fact, until now the FM model had been used only for the flight simulations in orbit with no boundary conditions. In our test, we decided to consider as boundary conditions the heat fluxes on each of the 6 faces of the satellite, calculated by another member of EntrySat team (see reference [2]). In particular, we used as values for the heat fluxes, the sum of solar flux, albedo flux, IR flux and friction flux. In this calculation, the orbit considered had the starting parameters (because the altitude varies) presented in Table VIII.

Semi-major axis	6581 km
Eccentricity	0,00051
Inclination	51,6389 °
ω	164,6135 °
Ω	-164,134 °
Mean anomaly	0 °
Date	01/01/2016 00h00min00s

TABLE VIII
PARAMETERS OF THE ORBIT THAT GAVE THE HEAT FLUXES

So, we took these measurements and used them as boundary conditions for the model nodes related to the satellite panels.

2) We imposed the boundary conditions in order to obtain the second model. The difference between this model and the previous one is that, in this case, we put the heat fluxes as boundary conditions also for the nodes related to the solar panels (in a proportional way).
3) In parallel, we have performed another simulation: in particular, we took the parameters of the orbit that the other member of the EntrySat team has used to get the heat fluxes (Table VIII), and put this trajectory in Thermica. The difference between this simulation and the other two is that in this last case the trajectory semi-major axis is fixed. So, the comparison can be done only for the first part of the simulation (when the altitude is approximately the same).

C. Results

The output of the simulation that we have used in this test are some .xls files created by Thermica which contain, for each node of the model, the temperature varying with time during the simulation.

For each model created, we have analysed the temperature of the node related to the batteries because they are the most critical component of the satellite.

D. Conclusion

As you can see from Figure 4 and in Appendix C, the temperature of the batteries is maintained in an acceptable range (maybe the use of heaters could be needed) at the beginning, with the temperature oscillating regularly within a stable range. However, at an altitude of approximately 120 km, the temperature rises suddenly and this will mark the end of life for the satellite.

In the first part of the simulations with heat fluxes as boundary conditions, the mean temperature is different from the one of the in-orbit simulations, as we can see in the appendix. If we impose the heat fluxes on the external panels and on the solar panels proportionally (model 2), the temperature is lower than the one of the in-orbit simulations. If we impose the heat fluxes only on the panels (model 1), the temperature is more similar to the in-orbit simulation. We have already verified that the units of measurement for the fluxes are correct (they are in W), so we are not sure why we see this difference, although we believe that considering the fluxes also through the solar panels is the logic option.

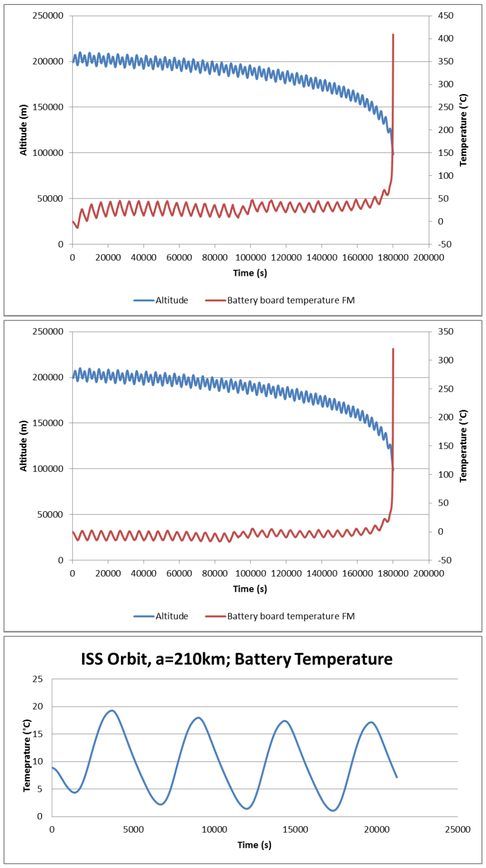


Fig. 4. Batteries board temperature evolution for model 1 (up), 2 (middle) and 3 (bottom)

The good news is that, for both simulations with variable altitude (with flux in the solar panels and without), we see that the point where the temperature rises suddenly is the same, i.e. about 120 km, so we can have now a better idea of when the satellite will finish to send data and the mission will be over.

VI. EPS BOARD HEATERS TEST AND THERMAL CONTROL TEST

A. Objective

Our last objective was to write in C the driver to test the functioning of the EPS board (NanoPower P31us board from GomSpace) heaters and the thermal control: its function is to manage the batteries temperature, which, as we explained before, are the most critical component of the satellite.

B. Work done

The starting point of this test was the version 542 of the satellite software. After some modifications, we created a new driver for the EPS board test, we tested it and we obtained the current last version of the software (version 549). In particular, the steps have been:

1) We created a new function, called *eps_GetHEATER(heater_status_t * heater_status)*

which can be used in the main program to get the status of the heaters, i.e. to know if they are ON or OFF.

2) We modified and put in the *eps.c* (see Appendix D) file the functions called *Initialize_Thermal_Control()*, *Reset_Thermal_Control()*, *Actuate_Thermal_Control(double Temp, int Heater_State)*, *Update_Range_TC(double Tmin, double Tmax)* and *Get_Temperature_Filtered()* which are used in the automatic thermal control. In particular:
   - *Initialize_Thermal_Control()* establishes what are the values of the minimum temperature (below which the heaters must be turned on, we used 24^oC and 32^oC for the test), of the maximum temperature (above which the heaters must be turned off, we used 27^oC and 35^oC for the test) and of the filtered temperature; in particular, the latter temperature is the effective temperature used during the thermal control, and it is defined as $T_{filtered} = 0.2 \cdot T_{measured} + 0.8 \cdot T_{filtered}$, and so its value is updated after each iteration;
   - *Reset_Thermal_Control()* resets the time during which the heaters have been on; in fact, the heaters cannot be ON for too much time, because it could be dangerous for the EPS board integrity;
   - *Actuate_Thermal_Control(double Temp, int Heater_State)* establishes if the heaters must be turned on or off depending on the filtered temperature;
   - *Update_Range_TC(double Tmin, double Tmax)* permits to modify the values of the minimum and maximum temperature;
   - *Get_Temperature_Filtered()* permits to get the value of the filtered temperature.

3) We modified the main program (called *main.c*, see Appendix D), splitting it up in 2 different parts:
   - in the first part, we checked if the housekeeping data lecture was working well (using the function *eps_GetHkT(eps_hk_t * eps_hk)*), if the heaters could be controlled manually (using the function *eps_SetHEATER(uint8_t Command, heater_status_t * heater_status)*) and their influence on the temperatures given by the sensors.
   - in the second part, we checked the automatic thermal control.

4) We configured properly the hardware and the software for the test (see Figure 5 and, for the description of the configuration, see reference [7]).

C. Results

The output of the test was the text that we obtained in the console and that you can see in the Appendix D.

D. Conclusion

After doing this test and looking at the text we obtained in the console, we can say that the driver works correctly. In fact, all the functions that we have created, modified and tested in the main file, work, as well as the automatic thermal control. So, the objective, which was that to turn on the heaters when the temperature is too low or when we command them to turn on, and to turn off them when the temperature is too high or when we command them to turn off, has been accomplished.

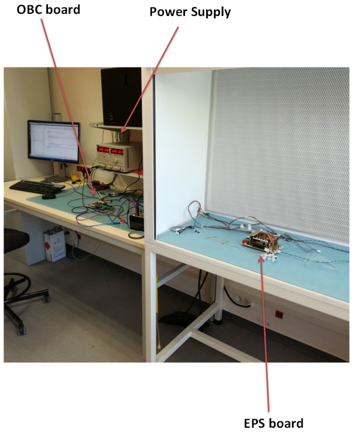


Fig. 5. Hardware and software configuration for the EPS board test

VII. FUTURE WORK AND PROSPECTS

About the thermal part, the next task to handle would be to perform a TVAC test on the FM and to compare the results with Thermica results (in the same way we have done with the STM), in order to validate the FM. If there are any discrepancies, it will be necessary to refine the FM because, as it is a model, it is not perfect. After that, the thermal part should be actually finished. About the EPS board, the next step would be to do a TVAC test and test the thermal control algorithm there.

VIII. ACKNOWLEDGEMENT

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