THERMAL MODEL FOR CUBESAT: A SIMPLE AND EASY MODEL FROM THE SWISSCUBE'S THERMAL FLIGHT DATA

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THERMAL MODEL FOR CUBESAT: A SIMPLE AND EASY MODEL FROM THE SWISSCUBE'S THERMAL FLIGHT DATA

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After the launch in the 23 September of 2009, SwissCube has downloaded a big amount of data from space until today, some of them are very interesting for education, and they can open possibilities of learning some important lessons for space subsystems and future cubesat's designs. In particular, here are taken into account four years of flight data coming from the temperature sensors of SwissCube that have collected more than 200 full orbits in terms of temperatures from solar panels and from inner parts as electronic boards and batteries. With more than twenty sensors and in accordance with the illumination data coming from the solar panels, this paper wants to present an interesting thermal model for cubesats. The model, based on the finite elements approach, describes the evolution of the temperature during the orbit of two or more nodes (thermal elements) taking into account time of illumination, light and eclipses. The math and the heat transfer's equations are here presented in order to show how to develop a reliable and easy thermal model without going further in a complex finite-elements software. The goal of the development of this simple model, indeed, is the student education. As it has been a student work, it can be reused for other student-cubesat's projects just manipulating some parameters or equations, having always an eye on how the thermal propagation works in space and how it is implemented in a software. The key points are the simplicity and the reliability due to validation from four years of thermal data coming from SwissCube. At the same time the possibility of increasing the complexity and the precision of the model with more than two nodes is still an open door. Results and simulations are here presented in accordance with a validation from the SwissCube's flight data, showing the pros and the cons of this model.

I. INTRODUCTION

With 10x10x10cm and a mass of less than one kilogram, SwissCube is the first pico-satellite completely developed and built in Switzerland in collaboration with several education Swiss institutions; the University of Neuchatel, the HES-SO and the FHNW took part in the development of the pico-satellite led by the Ecole Polytechique Federale de Lausanne. The 23th of September of 2013, it will be on orbit for 4 years after the launch from the Indian Satish Dhawan Space Center (inclination: 98˚, apogee: 725km, perigee: 700km). Swisscube was launched with the PSLV-C14 (Polar Satellite Launch Vehicle) as piggy-bag of the main Oceansat-2 Indian spacecraft for oceanographic monitoring. Other three CubeSats and two Rubin satellites were launched together with the Swiss picosatellite. BeeSat [9], from the TU-Berlin, had the purpose of on-orbit verification of newly developed micro reaction wheels for Cubesat. The primary mission of ITU-pSAT1 [8], from the Istanbul Technical University, was to examine the performance of an on-board passive stability system with a magnetic coil. The other German cubesat from the Universität Würzburg, UWE-2 [8], had the mission objective of demonstration of a newly developed Attitude Determination and Control system and the technology demonstration of a GPS on a Cubesat. RUBIN-9 consists of two Spacecrafts Rubin-9.1 and Rubin-9.2 weighing 8kg each and primarily used for the Automatic Identification System (AIS) for Maritime applications.

The SwissCube main goal was educational and to have flight data feedback: after almost four years of housekeeping data and analyses in comparison with the pre-flight tests made by students during the development, the project can be considered a great success. The second goal was to demonstrate that the airglow emissions are strong enough to be measured by an off-the-shelf detector, validating the concept for the development of a low-cost Earth sensor. The camera, that is still working, had a lot of reflecting issues due to a not complete and exhaustive characterization. From this and from the results of the payload we cannot assume that this goal was totally achieved

This paper, as student study, proposes an extremely simple thermal model based on a simplification of the finite-elements approach. The basic equations of the heat's transfer used will be here presented and described giving particular relevance to their assumptions and simplifications in order to remark that the model can be used as first iteration for a preliminary design of a CubeSat. However, its simplicity is not synonymous of poor reliability or low quality. In the paper the validation with the flight-data temperature is presented to show the reliability and quality of the model, underlining the pros and the cons of it. The model has an educational purpose in order to give an overview of the thermal behaviour of a CubeSat and a first iteration for the thermal subsystem for future pico-satellites.

II. SWISSCUBE

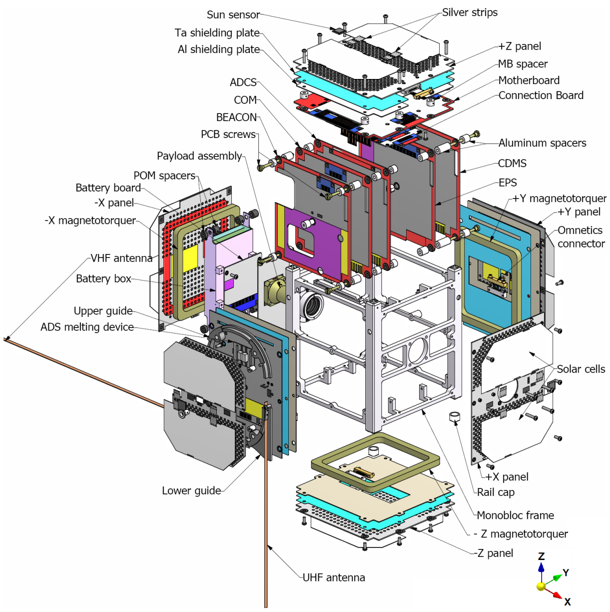

Figure 1: Exploded view of SwissCube

SwissCube is a pico-satellite with CubeSat specifications: 10x10x10cm for a mass of less than 1kg. The spacecraft has been designed, built and tested between the Ecole Polytechique Federale de Lausanne, at the Swiss Space Center, and other companies and universities of Switzerland. The baseline in the SwissCube's development has been the implementation of functional redundancy in the critical systems (with a very robust design) but not redundant systems to save mass and reduce complexity. The mission critical functions were those that ensured launch survival and basic housekeeping. This has been taken into account particular for the Electrical Power System (EPS), the Beacon Signal, the fabrication processes and structural design to survive the launch. Basic reliability considerations start with EPS for which partial redundancy and robustness have been implemented to maximize reliability. Redundancy is achieved by having separate batteries, charge and discharge circuits and solar cells. Robustness is achieved by the simplicity of the system that does not require any programmable controller. Each subsystem has its own board and own micro-controller. This architecture was well adapted for fabrication and tests of each subsystem independently. The COM, Payload, ADCS, and EPS subsystems all have a MSP430F1611 microcontroller, while the CDMS has an ATMEL ARM AT91M55800A OBC. However, since this microprocessor has no hardware I2C capability, it is linked to a MSP by an SPI data bus. Here a brief description of the subsystems on board, more details can be found in [2].

II.I Electrical Power System (EPS)

The EPS is spread over 9 electronic boards: the 6 faces of the satellite where 12 GaAs solar cells and protection diodes are soldered; a motherboard (MB) for the DC bus control, batteries and solar cells management; a battery board; and a power management board in charge of the power distribution, start-up sequence management, voltage and current measurements and beacon generation. The power is stored in two 1.2Ah lithium-Ion Polymer batteries (VARTA) inside a battery-box, which presents a thermal active control that (with a temperature sensor and a resistor) heats the subsystem with a 100mW when the temperature goes below the -5˚C and stops once reached the 5˚C.

II.II Attitude Control and Determination System

The architecture of the determination subsystem is based on: three ADXRS401 MEMS gyroscopes, 12 DTU sun sensors, one 3-axis HMC 1043 magnetometer. The actuators mounted are three magnetotorquers designed and built at the Swiss Space Center that run a B-dot controller, see [1] for results.

II.III Communication System

SwissCube has two links: one with high-power and high-rate link (for uplink and downlink), the other a low-power beacon signal. The first one is located on the COM board, while the second one generates a Morse code from the EPS board and transmitted by the Beacon board.

II.IV Structure

SwissCube's structure is compatible with the CubeSat standard, including access ports and deployment switches. However the structure is a not standard "monoblock" design selected on weight constraints and structural considerations. This approach had the disadvantage of increasing the complexity of the satellite's assembly procedures, however it served as secondary structure for the attachment of the Payload, PCB and external panels.

III. THE TEMPERATURE DATA

SwissCube has a various number of sensors, mostly for the Attitude Determination and for the EPS, but one of the most interesting data come from four years of temperatures downloaded. As shown and analysed in [1], the data stored cover almost four years of flight of SwissCube with a nice resolution over one or two orbits at each time. The sensors monitor both the external temperatures of the faces in direct contact with the Sun's illumination and the temperatures of inner PCB boards such as the MB, the EPS, or the Batteries. The temperature's data are the best feedback received from SwissCube because they give a large view of the temperatures during four years of flight and, as shown in [1], a lot of analyses have been done around them: from simple thermal considerations to ADCS considerations.

III.I The Sensors

There are several temperature sensors on board, but most of them are used as check for the functionalities of the circuits. All the sensors are detectors LM94022: Multi-Gain Analog Temperature Sensor with Class-AB Output. The LM94022 is an analog output CMOS integrated-circuit temperature sensor that operates at a supply voltage as low as 1.5 Volts. The temperature accuracy is of ±1.8˚C if operating in a range of -50˚C and 70˚C.

Two sets of temperature flight data are downloaded at each passage as housekeeping. The first one comes from the gyros, the magnetometers, the magnetotorquers and the MSP microcontrollers: they can give a maximum of 15min of recorded time with a non-constant time sample. The other is a set of measurements of maximum two orbits (196min) with a constant time sample of 5min. In this group there are measurements coming from: six sensors placed on the solar panels, giving the temperature of the faces; one is facing the external environment on the Z face (EXT); two sensors monitor the two batteries (BAT1, BAT2); one (MB) is on the EPS-motherboard (right next to the Z+ face); one (PCB) is placed on the EPS-Power Management Board (Y+ face); one (FRAME) is directly on the monoblock structure.

This group of measurements are the most interesting because can provide informations about the thermal behaviour of the satellite during one or two orbits, while the other measurements (taken just for 15min) have been used to post-process the gyros data downloaded due to their thermal hysteresis, or to check other processes. Further details can be found in [1].

Currently all the sensors are still operative without malfunctions.

III.II The Data

In this paragraph, we want to present the typical data that SwissCube stored during its life. It's important to show the temperatures measured in order to understand how the model has been designed and validated: some important assumptions have been taken from the analysis on the temperatures ([1]). The following graphs, [Fig.2] [Fig.3] and [Fig.4], are some examples of the temperatures of SwissCube in 2009, 2011 and 2012. [Fig.2] and [Fig.3] are both graphs showing the temperatures of the six faces of SwissCube with the solar panels. The two graphs present a nomenclature in which, as example, the positive Z face ([Fig.1]) is described as "ZP".

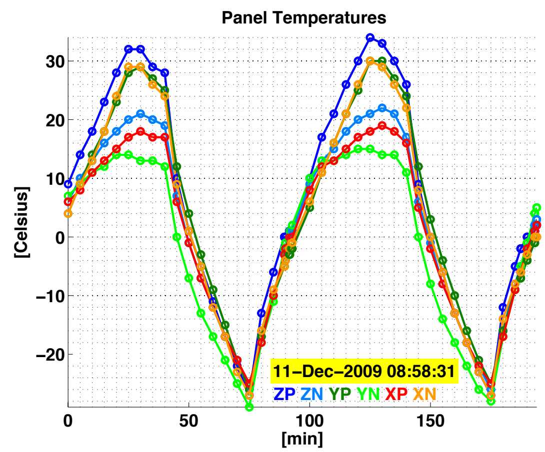

Figure 2: Solar Panels temperatures December 2009, tumbling at more than 600deg/s. ZP: Z positive face (dark-blue), ZN: Z negative face (light-blue).

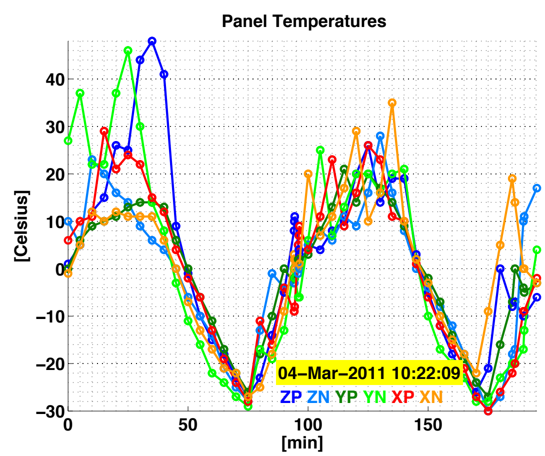

Figure 3: Solar Panels temperatures March 2011, rotating at less than 5deg/s. ZP: Z positive face (dark-blue), ZN: Z negative face (light-blue).

As described in [1], SwissCube was rotating at more than 600deg/s when deployed and it decelerate naturally to 100deg/ in more than one year. Moreover, after February 2011, the attitude control was turned on and the body started to de-tumble completely in 8days, reaching a final rotation of 1/2deg/s. These two conditions of very high rotation and de-tumbled motion have been matched even with the temperatures on the external panels.

First of all, we need to underline that the Sun illuminates and heats up the external faces: this means that the attitude is influencing the temperature of each face. During the end of 2009, [Fig.2], SwissCube was rotating at more than 600deg/s, and this is visible on the external temperature of the spacecraft. The body is rotating around its axis of maximum inertia, thus some faces are more illuminated and heated than the others (ZP-XN-YP are hotter than ZN-XP-YN). Moreover, as can be seen from the difference of [Fig.2] with [Fig.3], the body is rotating at high speed thus the faces have in 2009 those smooth paths; while in 2011 (rotating at 2deg/s) the faces have often temperature variations.

During the thermal model design we decided to take into account the data from the tumbled situation as first iteration, doing some assumption [sec.IV.I] on the model. The main point is to consider the CubeSat as one sphere with two nodes, one internal and one external as in [Fig.5]. Thus the external node should be representative of an equivalent sphere surface that emulates a surface of 6 faces as a CubeSat. We took into account the data of SwissCube when tumbling in order to describe an equivalent body without caring about the attitude. The next step of this study [sec.VII] will be to augment the number of nodes and re-modelling the parameters in function of different situations in which the body is highly rotating (using data as [Fig.3]), seeing differences from the different faces-nodes.

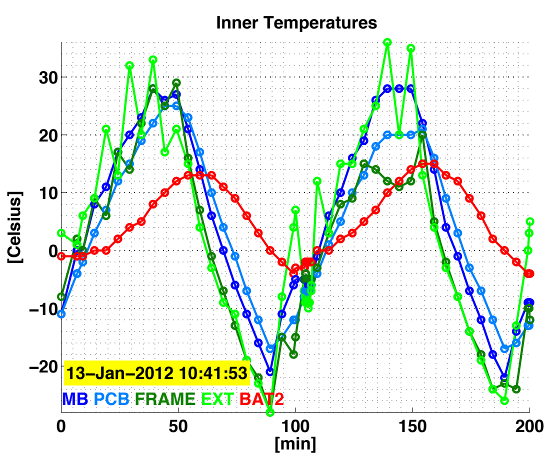

Figure 4: Temperatures inside SwissCube, Motherboard, PCB-EPS, Frame structure, External temperature, Battery (n°2)

The last data that we want to present are shown in [Fig.4]: SwissCube has other inner sensors mostly to check the functionality of the circuits and of the boards. Some of them can provide more than 15min of data and they are shown in [Fig.4]. The acronyms and the definition of them as already mentioned in [sec.III.I]: what we want to show is the behaviour of the inner parts in comparison with the external temperature of one face (EXT) or of the frame structure (FRAME). The frame sensor and the external sensor have not smooth path during two orbits as the MB or the PCB that are located in the body, due to their interaction with the illumination (dependence from the attitude). What we have discovered ([1]) is that inside the Cube the temperatures follow smooth paths due just to illumination and eclipse without any attitude issue.

From this, we decided to choose one of those internal sensors in order to find good parameters for the internal node of the model. Our focus has been moved immediately on the behaviour of the batteries.

As described, the batteries are inside a box that has copper layers that increase the thermal inertia, moreover, inside this box there is even an active thermal control that heats the batteries once the temperature is below the -5˚C, turning off once is over 5˚C. From these, we decided to model the inner node of the simulator as a battery.

III.III The illumination

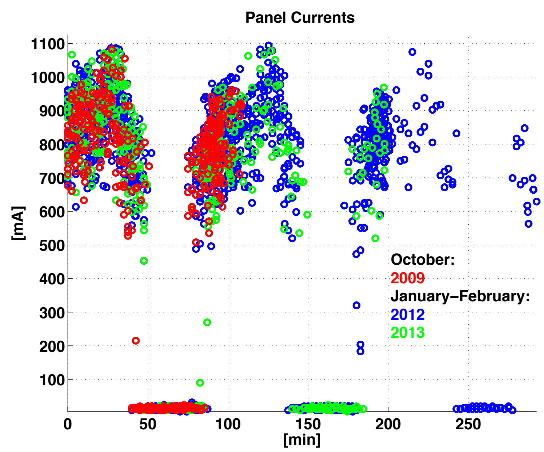

Figure 5: Sum of the panel's currents during the orbits; data from September-October 2009, and January-February 2012 and 2013

The Solar Panels give information on the currents stored: in [Fig.5] the sum of the panel Currents is tracked in one graph through 2009 (October), 2012 (January-Febrary) and 2013 (January-Febrary). It is interesting to underline that the body is illuminated during the light passages with a non-constant input. If looking at the sum of the currents, from one eclipse to another, the currents vary from a 60% (600mA) to a 100% (1100mA) and again to a 60% in 60min of facing the Sun. This effect is present on each orbit and independent from the attitude of the pico-satellite, because in [Fig.5] are shown data from 2009 and from 2013 in which SwissCube was rotating respectively at 650deg/s and 2.5deg/s.

An example of how the external temperatures react in comparison with the (total) illumination coming on the body can be seen in [Fig.6]. It is evident that the illumination is not constant and affects the temperatures of the surfaces, creating some plateaus on the temperatures paths.

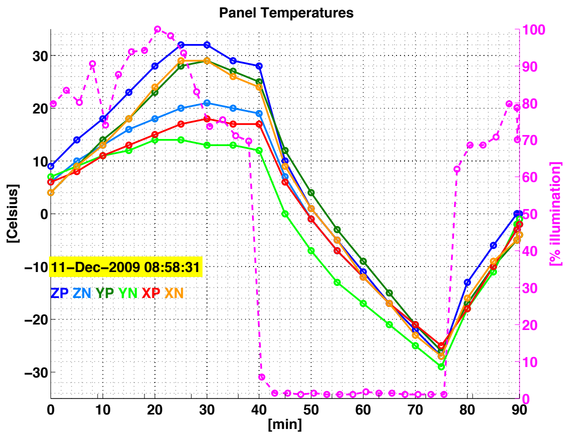

Figure 6: Temperatures of the Surfaces in comparison with incoming total illumination.

From this point it has been defined that the input of the heat from the Sun is not constant during the orbit. This has been taken into account into the model varying the Sun's heat from 60% to almost 100% through the illuminated time.

IV. THE MODEL: TWO NODES PROBLEM

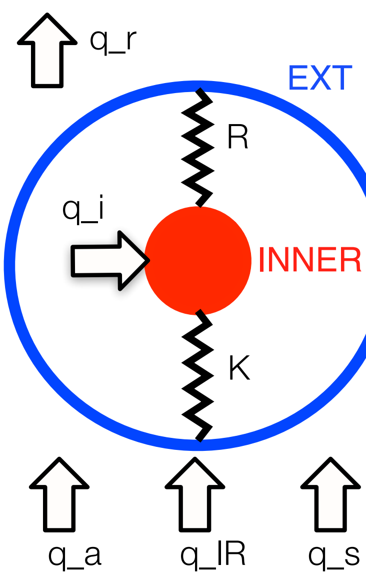

Figure 7: Two nodes model

The model that we decided to take into account is based on the finite element approach but extremely simplified: just two nodes are used, one representing the equivalent external surface and one representing an internal area. The reason of this choice comes from the goal of this study. The idea is to keep the model as simply as possible but modelling all the parameters and the characteristics to follow as close as possible the flight data collected on orbit. In this way an easy and understandable thermal simulator can be used both for preliminary analysis without going deep into complex FEM equations, and for education, trying to use few principals of the thermal environment. The assumptions taken are shown in [sec.IV.I] and the parameters used and tuned are presented in [sec.IV.II].

The target of a simulator for a thermal subsystem is to determine the evolution with time of its temperature distribution. Currently, two widespread approaches exist for that purpose, both start from the FEM (finite element model): one based on integrators, the other one based on the interpolation. We took into account the first approach in order to follow the basic thermal principles without focusing in complex mathematical systems ([7]).

This model starts from a discretization of the body in a network of nodes (blue and red from [Fig.7]) and links (black). Each node is an isothermal volume where the heat can be stored, and they have their own capacitance (C_i) and heat source. The links are here thought as resistances between two nodes that allow the heat to flow from one to the other. It can be conductive or radiative. Convective fluxes are here neglected. The network here presents just two nodes and one link of conductive flow (K) and one radiative (R).

[Fig.7] is the sketch of the model in which the two nodes are highlighted in red and blue: as mentioned one (blue) is in contact with the external environment, while the other (red) is representing an inner equivalent part of the spacecraft. The links are conductive and radiative: the upper one is representing the radiative flux while the lower represents the conduction.

At each node (same approach for the FEM), it must be applied the heat conduction (Fourier's law: first term on the right of [Eq.1]) and the radiation (Stefan Boltzman's law: second term on the right of [Eq.1]): in this way at each node can be assigned a differential equation that can describe the evolution in time (if integrated) of its temperature distribution ([7]).

$$C_i \frac{dT_i}{dt} = \sum_{i \neq j} K_{ij}\left(T_j - T_i\right) + \sum_{i \neq j} R_{ij}\left(T_j^4 - T_i^4\right) + q_i \qquad [1]$$

$$i, j = 1, \ldots\ldots, n$$

n is the number of nodes in the network: where T_i, C_i, and q_i are the temperature ([K]), the capacitance ([J/K]) and the heat source ([W]) of node i. K_{ij} and R_{ij} are respectively the conductance ([W/K]) and the radiative exchange factor ([W/K^4]) between nodes i and j. The values of C_i, K_{ij} and R_{ij} depend on the physical properties and the geometry of the system, and in this case they have been tuned looking at the results of the flight data ([sec.IV.II]).

In this model, [Eq.1] can be applied to the two nodes. For the internal node it can be rewritten as:

$$C_{\text{int}} \frac{dT_{\text{int}}}{dt} = K\left(T_{ext} - T_{\text{int}}\right) + R\left(T_{ext}^4 - T_{\text{int}}^4\right) + q_{\text{int}} \qquad [2]$$

Where the conductive flow, the radiative flow and an internal heat source are applied on the internal node (q_{int}). The conductive and the radiative flows comes from the interaction with the external node. The q_{int} is the internal source of heat (q_i on [Fig.7]) produced by the resistance of the active thermal subsystem. As described further, this node is assumed as the box of the batteries in which an active control of the temperature is on when the batteries reach the -5˚C and turned off when they reach 5˚C. The resistance inside the box has been measured during the active control to produce a heat between 100mW and 170mW.

[Eq.1] can be rewritten for the external node as:

$$C_{ext} \frac{dT_{ext}}{dt} = K\left(T_{\text{int}} - T_{ext}\right) + R\left(T_{\text{int}}^4 - T_{ext}^4\right) + q_s + q_p + q_a + q_r \qquad [3]$$

[Eq.3] is based on the same heat transfer between the external node and the internal node as [Eq.2], and added the other flows coming from the environment. These two equations, once defined all their parameters, must be integrated with a good integrator: we used the Runga-Kutta 4-5 proposed by Matlab (ODE45).

The four external arrows in [Fig.7] represent the other flows of heat coming from the main sources in space. The External node receives as input the heat coming from the Sun (q_s), the heat coming from the Infrared emission of the Earth (q_IR) and the heat coming from the albedo, the reflection illumination of the Sun on the Earth's surface (q_a), [sec.IV.II]. The spacecraft is even radiating heat to deep space, represented by the upper arrow in [Fig.7].

The four fluxes are described in the next equations:

$$q_s = A_s \alpha_s J_s \qquad [4]$$

$$q_p = A_p F_{s-p} \varepsilon \sigma_n T_p^4 \qquad [5]$$

$$q_a = A_p F_a \alpha_s J_s a \qquad [6]$$

$$q_r = A_r \varepsilon \sigma_n T^4 \qquad [7]$$

The flow coming from the Sun, [Eq.4], is based on the Solar constant (J_s) that has its Worst Cold Case at $1323 W/m^2$ and its Worst Hot Case $1423 W/m^2$ depending on the solar activity, with a mean values of $1366 W/m^2$. The heat that the spacecraft receives depends by the Area projected into the direction of the Sun (A_s) and by the coefficient of the absorbance (α_s).

[Eq.5] has been used to model the heat flow for the emissions of the planet in the Infrared wavelength. This flux depends by the season and by the characteristics of the ground: once fixed the area projected to the Planet (A_p), the Factor of view between the surface and the spacecraft (F_{s-p}) and the terms from the Planck's law and the Lambert's law ($E=\sigma_n T_p^4$ where σ_n=5.67e-8 W/m^2K^4 and T_p=288K), just the emissivity (ε) must be fixed. This changes in function of the ground's characteristics, from 0.99 for a tropical forest to 0.88 for dry sandy desert.

Similar to the heat coming from the Sun, the heat of the Albedo, reflection of the Sun's illumination on the ground and on the Earth's atmosphere, can be discretized as in [Eq.6]. Again the area projected (A_p), the factor of view between the area and the planet (F_a), the absorbance (α_s), the Solar constant (J_s) are in the equation, and then the albedo coefficient that depends on the reflective surfaces (for preliminary evaluation a=0.34).

The last [Eq.7] defines the last contribute of heat to a spacecraft, the radiation of the heat to the deep space. This flux is a radiative heat transferred from the body at temperature T to the deep space at 0K. Even in this equation, the heat is depending by the emissivity (ε) and the radiative area (A_r).

These flows of heat are dependent on the orbit on the minutes of illumination and on the eclipse. It's clear that once in eclipse the Sun is not illuminating the body, as the albedo, that is just a reflection of it. But this is not true for the IR emission of the planet, that is not dependent from the light but from the local temperature of Earth's surface and the amount of cloud cover, however the global annual average basis is fairly well maintained ([3] and [4]). In this way the q_p described in [Eq.5] has been assumed constant during one orbit.

Moreover, the input of q_s is not just ON-OFF once passing from light to eclipse: this has been found in the general behaviour of the solar panel's currents. Looking at [Fig.5] and [Fig.6], the illumination (sum of the currents of all the solar arrays) is varying from 60% to 100% to 60% again. This behaviour has been considered in the q_s following the same path 60%-100%-60%.

IV.I Assumptions

The first assumption refers to the external node and the surface that it should monitor. This node, as already mentioned, is representing the total external surface of the spacecraft. This means that the temperature simulated is a mean value reached by each surface. Thus the results can be taken as reference for a preliminary study on the temperatures reached by the surfaces. [Fig.2] is taken as reference to set and tune the parameters for the external node: we have decided to take the tumbling mode as first attempt and reference because closer to the goal of the external node, to give a mean value of the surface without caring about the attitude of the spacecraft itself and the temperature of each surface.

As mentioned, the internal node has been assumed as inner part of the spacecraft and it represents (as for SwissCube) an inner battery-box actively thermally controlled. In this way the heat produced by the resistance inside the battery-box has been setup to turn off once the temperature is over 5˚C and turn on when below the -5˚C. While turned on, in SwissCube, it produce between 100mW and 150mW: in the model it has been used 100mW as q_i.

The two nodes have been considered as two concentric spheres: the external one (in which the external node is places) has a radius of $r_{ext}=(S/(4\pi))^{1/2}$ function of the external surface (in case of a Cubesat 6*10cm2, so $r_{int}\simeq 7cm$) while the inner sphere has an arbitrary value (here chosen as 1cm). Using this assumption the K and the R coefficients of [Eq.2] or [Eq.3] can be assumed as:

$$K = \frac{4\pi\lambda \cdot r_{\text{int}} r_{ext}}{(r_{ext} - r_{\text{int}})} \qquad [8]$$

$$R = \frac{4\pi r_{\text{int}}^2}{\frac{1}{\varepsilon_{\text{int}}} + \frac{1-\varepsilon_{ext}}{\varepsilon_{ext}}\left(\frac{r_{\text{int}}}{r_{ext}}\right)^2} \qquad [9]$$

Where the emissivity (ε_{int} and ε_{ext}) have been tuned considering the flight data and the theoretical values. λ is the heat conductivity ([W/(mK)]). These parameters and the capacitances (C_{int} and C_{ext}) have been assumed constant during the time to simplify the model.

IV.II Parameters

In the previous section we have presented several parameters coming from the equation of the heat transfer. Here we want to present briefly all the parameters tuned for the validation with the SwissCube flight data.

	Definition	Value
S	CubeSat Surface	$0.06m^2$
A	Total Area for heat transfers: =S+Antenna's Surfaces	$0.06462m^2$
A_s	Area facing the Sun	$0.03231m^2$
A_p	Area facing the Planet	$0.03231m^2$
A_r	Radiative Area	$0.06462m^2$
F_{s-p}	View Factor between S/C and the Planet	0.5
F_a	View Factor for the Albedo	0.5
J_s	Mean of the Sun Power incident	$1366W/m^2$
$\varepsilon_{ext}=\varepsilon$	Emissivity Surface	0.9
ε_{int}	Emissivity internal part	0.05
σ_n	Stefan Boltzman Constant	$5.67e\text{-}8W/m^2K^4$
a	Mean albedo value	0.34
T_p	Planet Temperature	288K
α_s	Absorbance Coefficient	$0.65W/m^2$
C_{int}	Internal (node) Capacity	80J/K
C_{ext}	External (node) Capacity	570J/K
λ	Heat conductivity	0.25 W/mK

Table 1: Tuned Parameters

Applying all these parameters to the previous equations [Eq.4], [Eq.5], [Eq.6], [Eq.7], the maximum total heat received on to the external node is of 35W (when the illumination is higher), while during the eclipse the heat is just 5W.

V. RESULTS

In this section we want to show the results achieved using the two-nodes model designed and described previously. The data of the 11.12.2009 have been used to validate and tune the model. These data have temperatures for the external solar arrays and for some inner parts. In the simulation just the external temperatures and the temperature of one battery have been used. As shown in [Fig.2] the six temperatures have smooth paths due to the attitude of SwissCube that is rotating at almost 600deg/s: in this way the illumination is distributed on the faces without having high peaks of temperatures as in a slow rotation in [Fig.3].

Moreover, the model has just one external node, thus we took the mean of the six external temperatures (light blue line in [Fig.9]).

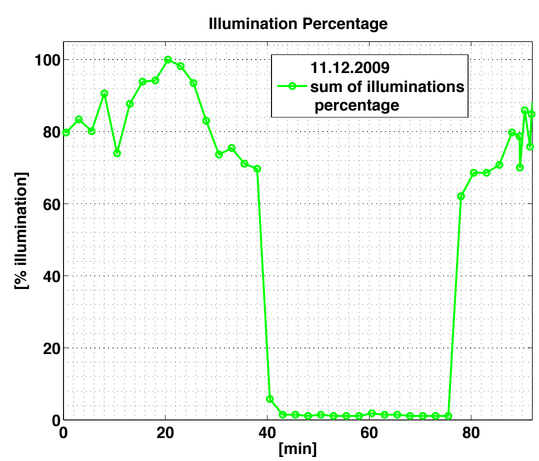

Figure 8: 11.12.2009 Percentage of total illumination on SwissCube (flight data).

As already mentioned in [sec.III.III] and shown in [Fig.5] and [Fig.6], the total illumination when facing the Sun is not constant. In [Fig.8] this is clear and we have applied to the model the same behaviour: taking an interpolation of these data, the heat coming from the

Sun and the albedo have the same behaviour of the function interpolating the data shown in [Fig.8].

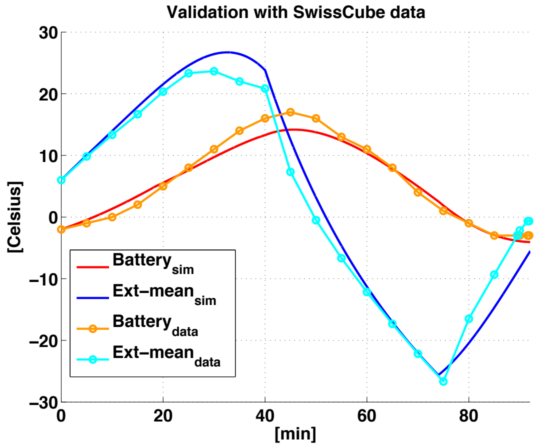

Figure 9: Results of the simulation with the two-nodes model (red and blue) in comparison with the flight data of the 11.12.2009 of the mean external temperature and the battery (orange and light blue).

The results obtained show the performances of the model: an overshoot of 4˚C at 35-40min has been encountered with the external node and another one at the end of the simulation has been found of 6˚C. For the battery and the inner node the difference is just of 3˚C at the top of the temperature of the battery at 45min.

As already mentioned, we took into account for the tuning of the parameters just the situation in which the body was highly rotating, thus the faces did not be influenced by the attitude: however in the next results it is highlighted that the model can be reliable as trend of the mean temperature of the pico-satellite even for slow rotations in which the attitude cannot be totally neglected.

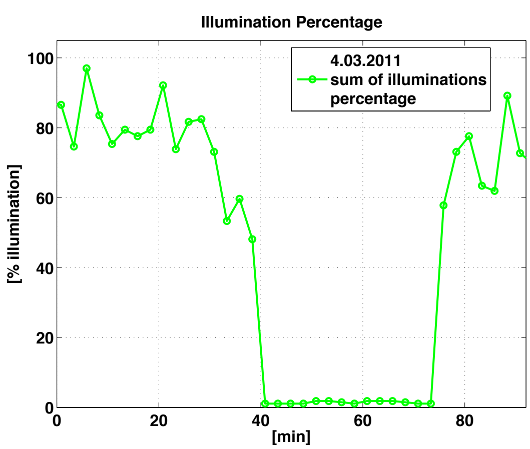

Figure 10: 04.03.2011 Percentage of total illumination on SwissCube (flight data).

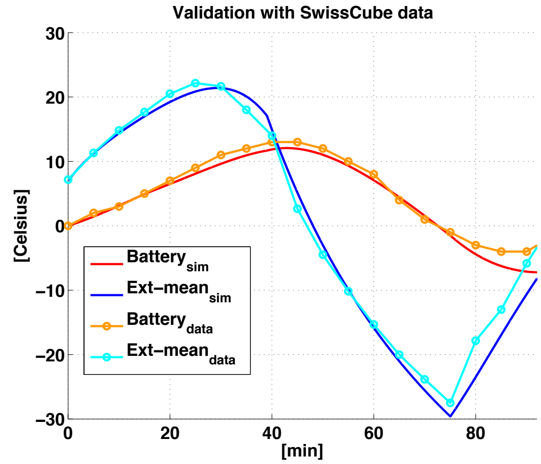

Figure 11: Results of the simulation with the two-nodes model (red and blue) in comparison with the flight data of the 04.03.2011 of the mean external temperature and the battery (orange and light blue).

As in the first simulation, the total illumination used as input (in percentage) is in [Fig.10]. [Fig.11] shows the results of the simulator (dark-blue for the external-node, red for the battery-inner-node) in comparison with the mean temperatures of the external temperatures of the 4.03.2011 ([Fig.3]). The results are consistent even if the model has been implemented basing on the high-tumbling situation ([Fig.2]). This confirms that the assumption of the external node that is equivalent to the mean temperature of the satellite's surface is reliable.

Considering that the light-blue data are just a mean value and all the LM94022 sensors have a ±1.8˚C if operating in a range of -50˚C and 70˚C, the current results can be considered reliable for a preliminary study and evaluation of the temperature for a cubesat, without taking into account the attitude problem.

VI. ANALYSES RESULTS

We used the same setup of the two nodes model to look at possible results of temperatures for a CubeSat changing the orbit. We took into account a circular orbit of 450km of altitude, with the same inclination of SwissCube. The STK-AGI simulator gave the approximate time of illumination and of eclipse for different Sun-Synchronous orbits. Three examples of orbits have been choosen: 12am-12pm, 10am-10pm and 8am-8pm. The first two examples maintain during one year more or less the same time of illumination and of eclipse, while the 8am-8pm changes during the year. For this orbit a Worst-Hot Case (WHC) and a Worst-Cold Case (WCC) have been characterized depending on the two light's time and eclipse's time: the WHC has 72min of light and 22min of eclipse, the WCC has 63min of light and 31min of eclipse. Between these two cases the CubeSat can have different situation due to the variation of the eclipse's time between 22min and 31min.

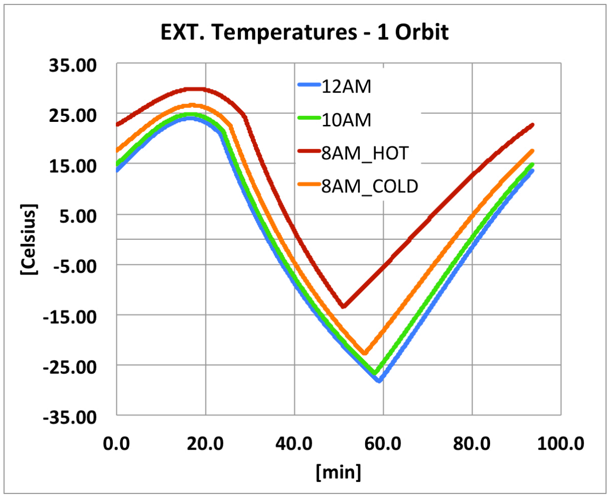

Figure 12: Temperatures of the External Node for different Sun Synchronous Scenarios, using the Two-Nodes Model

[Fig.12] shows the results for one orbit simulation with the two nodes model taking into account different scenarios of the Ascending node. For the external Node there is a big difference between the 8am case from the other, showing that the mean temperature of the surface tends to increase in this Scenario.

It is important to remember that those results do not take into account the attitude and different surfaces, thus looking at [Fig.3] a possible range of temperatures of the surface can be ±20˚C from the paths obtained.

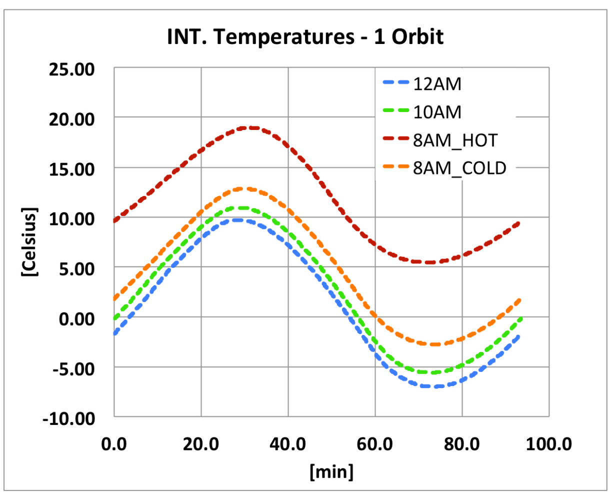

Figure 13: Temperatures of the Internal Node for different Sun Synchronous Scenarios, using the Two-Nodes Model.

More interesting are the results coming from the node that simulates the battery box ([Fig.13]). For the 8am scenario, the battery can be controlled passively due to the temperature reached. Taking into account the same model of the thermal control used for the validation, in which a 0.1W is applied until +5˚C once the temperature goes below the -5˚C, the 12am and the 10am still need the 0.1W of heat while the 8am not. This aspect could be very interesting for future CubeSat in order to save power and complexities or either to highlight the difficulty to use some scenarios of orbits or technologies.

VII. DISCUSSIONS AND FUTURE WORKS

In this paper a very simple model has been presented showing its pros and cons. In the pros the simplicity and the reliability are the main issues, while as cons the model cannot be used up to now to go deeper into the details such as determining the face's temperatures as function of the attitude. Indeed this is the next step for the model, using the attitude data analysed ([1]) for SwissCube to interpolate the temperatures of the faces with the attitude, the rotations and each single characteristic of the faces taking into account as examples the antennas as further surface of heat transfer. In this way the model should change from just two nodes to seven or more nodes in function of the interest of the point to monitor. Seven nodes should be the first step as six external faces and still one internal node, just to implement the attitude and the shadowing at each face.

However, the results in [sec.V] show that the model is reliable: the two examples confirm that the model can be used as prediction of the mean temperatures (external and internal) of a CubeSat whatever the attitude condition of the body are (highly rotating or not).

VIII. CONCLUSIONS

The goal of this student study was to develop a simple thermal model based on the flight data coming from SwissCube. Due to the large number of sensors mounted on board this model have been done as well as further improvements on the precision of this simulator.

The model has as main aim to be simple and based on the thermal equations and on the basis of the finite elements methods (FEM). As shown, the FEM approach has been simplified just to a two nodes structure: external and internal.

The idea has been of creating this simulator for education, without going deeply into a complex FEM model and its problematic settings, but just to use few equations of the thermal transfer and of the space environment to understand the background and to do a validation of the concept.

The simulator is kept simple for education and for an easy setup.

The model can be used as very first iteration for the thermal subsystem in phaseA studies of feasibility for future CubeSat as shown in [sec.VI], in order to make the first trade off solutions for thermal subsystem or power budgets determining the mean possible temperatures of the Satellite.

The results show ([sec.V]) that the simulator is reliable for predictions of the mean temperatures of a CubeSat (external and internal part) whatever the attitude condition of the body are (highly rotating or not).

As discussed the simplicity is both the pros of this concept and the cons, because some of the assumptions considered cannot be neglected in further and detailed analysis on the thermal subsystem.

From this discussion we have either proposed the next steps necessary to improve the model for a detailed and reliable thermal model for CubeSat.

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