On the thermo-electric modelling of smallsats

Alejandro M. Gomez-San-Juan[1], Javier Cubas[2] and Santiago Pindado[3]
Instituto Universitario de Microgravedad "Ignacio Da Riva" (IDR/UPM)
Universidad Politécnica de Madrid (UPM), Madrid, 28040, Spain.

Correct thermal modelling is crucial for smallsats. They can experience higher variations of temperatures and their components usually have a lower range of safe operating temperatures, especially if they are COTS (Commercial-Off-The-Shelf). This can make the thermal design more difficult and also, in certain aspects, very different when compared to bigger satellites. One of the main differences is the modelling of solar panels. Large satellites have control systems that guarantee that solar panels always operate at the maximum efficiency voltage. Therefore, one hypothesis that can be used in thermal models is that the efficiency of the panels only depends on the temperature. On the other hand, the electrical system of small satellites is usually very simple, often based on Direct Energy Transfer (DET). In these satellites, the operating voltage is not optimal, but mainly depends on the battery voltage. As a result, the previous hypothesis is no longer valid, and it is necessary to consider that efficiency depends on both the temperature and the operating voltage. This is an important change, and not considering it can lead to differences between modelled and real temperatures that greatly exceed safety margins. For correct modelling of DET satellites, one solution is to integrate the solar panel thermal and electrical models, in order to calculate the real efficiency at which it operates. However, this is not simple, since the electrical problem of a solar panel has many unknowns and implicit equations that complicate its resolution. In this work, the authors propose a simple methodology for thermo-electric modelling using only the solar panel parameters provided by the manufacturer. This methodology can be easily integrated into complete thermal models of smallsats using thermal analysis software. Simulation results for a smallsat mission, including differences in temperatures between thermo-electric and traditional modelling are also presented.

Nomenclature

α = solar absorptance
α_{Isc}, α_{Imp}, α_{Voc}, α_{Vmp} = variation coefficients of the corresponding parameter with the temperature
η = efficiency of the solar panel
κ = Boltzmann constant
ρ = solar panel reflectance
a = ideality factor
C_P = thermal capacitance of the solar panel
DET = Direct Energy Transfer
G = solar irradiance
GL = conduction heat exchange coefficient
GR = radiation heat exchange coefficient
I = solar panel's output current
I_{sc} = short circuit current
I_{mp} = maximum power current
I_{pv} = photocurrent
I_0 = saturation current

[1] Thermal Engineer, Instituto de Microgravedad "Ignacio Da Riva", alejandro.gomez@upm.es.
[2] Assistant Professor, Instituto de Microgravedad "Ignacio Da Riva", j.cubas@upm.es.
[3] Associate Professor, Instituto de Microgravedad "Ignacio Da Riva", santiago.pindado@upm.es.

LTDN	=	Local Time Descending Node
MCRT	=	Monte Carlo Ray Tracing
MPP	=	Maximum Power Point
MPPT	=	Maximum Power Point Tracking
n	=	number of series-connected cells within a solar panel
q	=	charge of the electron
Q_{S-P}	=	solar heat flux on the solar panel
Q_{A-P}	=	albedo heat flux from the planet on the solar panel
Q_{E-P}	=	infrared heat flux proceeding from the orbited planet
R_s	=	series resistor
R_{sh}	=	shunt resistor
SSO	=	Sun-Synchronous Orbit
T	=	temperature
T_P	=	temperature of the solar panel
V	=	solar panel's output voltage
V_{oc}	=	open circuit voltage
V_{mp}	=	maximum power voltage
V_T	=	thermal voltage
W	=	Lambert function
W_0	=	positive branch of the Lambert function
W_{-1}	=	negative branch of the Lambert function

I. Introduction

THE proper estimation of the available power per orbit (normally extracted by means of photovoltaic systems) of small spacecrafts is key to the mission success. Besides, an accurate modeling of thermal effects is also equally important to the mission. The available power is directly related to the efficiency of the solar panels, η, which depends on the operational point of the solar panel. Some spacecraft have Maximum Power Point Tracking (MPPT) systems to ensure the solar panel is operating at the Maximum Power Point (MPP). However, small spacecraft do not include such systems, the solar panel operation point being conditioned by the battery voltage. This power regulation is called Direct Energy Transfer (DET). Additionally, the efficiency of the solar panels' performance is also affected by the panel temperature and the solar irradiance, as its performance curve (that is, the current-voltage curve) is altered by changes in both parameters.

Considering the combined effects of electrical and thermal behavior it is logical to study spacecraft power systems performance by means of a coupled analysis that includes this interaction. Unfortunately, small spacecraft mission analysis does not include such considerations, as it is assumed that voltage changes do not affect efficiency.

In the present work, a simple methodology for thermo-electric analysis is proposed. In addition, a thermo-electric model of a 50-kg satellite, the UPMSat-2 mission[1], has been used as case study in order to analyze the coupled behavior of the temperature and the power efficiency of the solar panels. This is a 2-year mission 50-kg satellite that is prepared to be launched in March 2020. Its more relevant characteristics are:

- Orbit: Sun-Synchronous Orbit (SSO). 10:30 LTDN orbit. Altitude: 525 km.
- Dimensions: 0.5 m x 0.5 m x 0.6 m.
- Attitude control: Magnetic. Based on SSBV magnetometers and ZARM magnetorquers[2–4].
- Passive thermal control.
- Power: Solar panels made of SPVS-5 Selex Galileo modules[5]. SAFT Batteries Li-ion battery. DET.
- On-board electronic box (computer) designed by TECNOBIT S.L.
- Communications: 4 monopole antennae system. Link at 436 MHz.

The present work is organized as follows: in Section II the thermo-electric problem of spacecrafts is outlined. The modeling of the solar panels is described in Section III, the results being included in Section IV. Finally, the conclusions are summarized in Section V. An Appendix with relevant information on the Lambert function is included at the end of this work.

II. Thermo-electric problem of solar panels

The mathematical model that describes the thermal problem of a solar panel orbiting planet Earth is the following one:

$$C_P \frac{\mathrm{d}T_P}{\mathrm{d}t} = Q_{S-P} + Q_{A-P} + Q_{E-P} + \sum_j GL_{Pj}(T_j - T_P) + \sum_j GR_{Pj}(T_j^4 - T_P^4) - \sigma GR_{PE} T_P^4 + \sigma GR_{P\infty}(T_\infty^4 - T_P^4) \,. \tag{1}$$

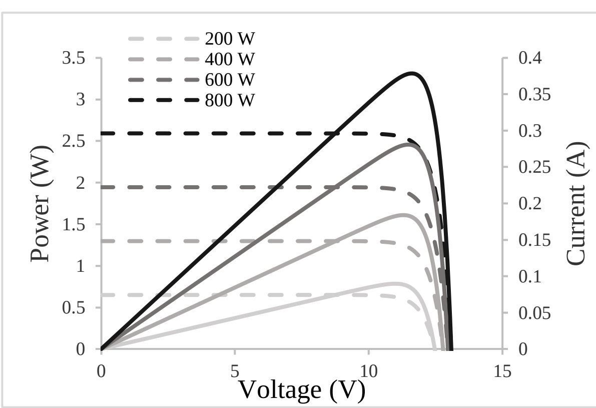
This equation is the energy balance applied to the solar panel in the lumped parameter approach, in which the spacecraft under study is discretized in nodes with equivalent thermal properties. The equation states that the change in the internal energy of the panel (its heat capacity C_P times the variation of the panel temperature with time $\mathrm{d}T_P/\mathrm{d}t$) equals the net sum of heat fluxes of the panel with its environment. The first three terms are the incoming external fluxes: Q_{S-P} is the solar heat flux on the panel, Q_{A-P} is the albedo heat flux from the planet on the panel and Q_{E-P} is the infrared heat flux proceeding from the orbited planet. The summation terms are the heat exchange by conduction (GL) and radiation (GR) with the other j nodes composing the thermal model of the spacecraft. The last two terms are the heat radiated in the infrared to the Earth ($-\sigma GR_{PE}T^4_P$) and the net heat radiated to deep space ($\sigma GR_{PE}(T^4_\infty - T^4_P)$). The radiative external loads (Q_S, Q_A, Q_E) and the radiative heat exchange coefficients (GR) are usually calculated by the thermal software using a Monte Carlo Ray Tracing (MCRT) algorithm. However, not all the energy a body receives is absorbed, part is reflected and, in solar cells, part is converted to electricity. The real heat absorbed by the solar cell, Q_{S-P} and Q_{A-P}, can be calculated in terms of the received heat loads (Q^*_{S-P} and Q^*_{A-P}):

$$Q_{S-P} = Q^*_{S-P}(\alpha - \eta) = Q^*_{S-P}\alpha_{eff} \,, \tag{2}$$

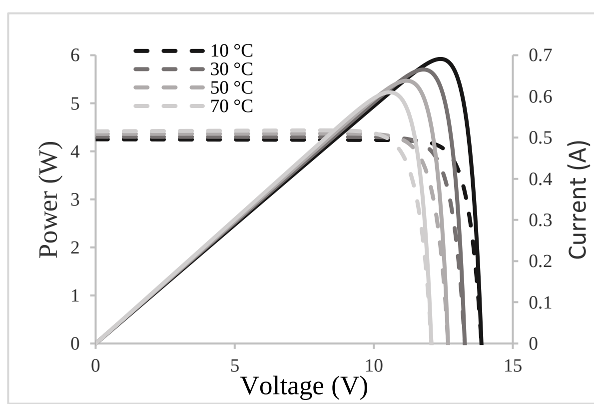
$$Q_{A-P} = Q^*_{A-P}(\alpha - \eta) = Q^*_{A-P}\alpha_{eff} \,, \tag{3}$$

where η is the efficiency of the solar panel, that is, the fraction of energy transformed into electric power by the panel and α is the solar absorptance. For an opaque material $\alpha = 1 - \rho$, where ρ is the panel reflectance. The equation can be simplified using the effective solar absorptance, α_{eff} that is obtained by subtracting the cells efficiency, η, to the actual solar absorptance, α. As triple junction cells produce energy from all the solar wavelength[6], albedo has been considered as a source of energy and corrected with cell efficiency.

Therefore, the thermal problem is coupled with the electrical problem through the efficiency of solar cells: η. This efficiency can be considered constant and equal to that which the manufacturer provides for ideal conditions, but it would be a very bad approximation that will probably yield thermal results far from the real ones. To obtain a thermal model as close as possible to reality, it is advisable to understand how the power production of the panels works, and on what their efficiency, η, depends.



(a)



(b)

Figure 1 Effect of irradiance (a) and temperature (b) variations on solar panel power (solid lines) and current (dashed lines) curves.

See in Figure 1 the power-voltage curve and the current-voltage curves of a panel for different temperatures and for different irradiations. As it can be observed, the maximum available power varies with temperature, T, being lower as this one increases. Both the maximum power current, I_{mp}, and the short circuit current (null voltage), I_{sc}, are proportional to the irradiance, G. However, the maximum power voltage, V_{mp}, and open circuit voltage (zero current), V_{oc}, hardly vary with G. Finally, both voltage and current values at these characteristic points (open circuit, short circuit and maximum power), are very dependent on the temperature, lowering the voltage levels and raising the current levels when the temperature rises. All these properties can be expressed as[7–9]:

$$I_{sc} = \frac{G}{G_0}\left[I_{sc0} + \alpha_{Isc}\left(T - T_0\right)\right], \tag{4}$$

$$I_{mp} = \frac{G}{G_0}\left[I_{mp0} + \alpha_{Imp}\left(T - T_0\right)\right], \tag{5}$$

$$V_{oc} = V_{oc0} + aV_T \ln\frac{G}{G_0} + \alpha_{Voc}\left(T - T_0\right), \tag{6}$$

$$V_{mp} = V_{mp0} + aV_T \ln\frac{G}{G_0} + \alpha_{Vmp}\left(T - T_0\right), \tag{7}$$

where α_{Isc}, α_{Imp}, α_{Voc} and α_{Vmp} are the coefficients that define the variation of the corresponding parameter with the temperature, T, the subscript “0” indicating values at reference conditions. All this information is normally given by the solar cells’ manufacturer. $V_T = nkT/q$ is the thermal voltage, n being the number of series-connected cells of the photovoltaic device (it should be noted that a triple-junction cell behaves like three cells in series, so in the case of triple-junction cell panels this number must be multiplied by 3), k the Boltzmann constant, T the temperature of the solar cells and q the charge of the electron. Finally, a is the ideality factor of the diode. This parameter normally varies between 1 and 2, but an acceptable approximation can be obtained for almost any panel with an approach based on the technology. In the bibliography[10] a value 1.2 is suggested for Si-mono and 1.3 for Si-poly and GaAs cells.

All these considerations are not necessary in the case of a solar panel with controlled voltage, since the maximum efficiency of the solar panel can be considered linearly decreasing with temperature, through a constant, α_η, which is usually provided by the manufacturer. In that case, it would be enough to complete Equations (2) to (3) with the efficiency, η, provided by:

$$\eta\left(T\right) = \eta_0 - \alpha_\eta\left(T_0 - T\right), \tag{8}$$

where only the temperature influences the efficiency. This approach is correct in case the solar panel operates at optimum voltage, something that usually occurs in large satellites, or in a ground installation. But that is not true in the case of small satellites with Direct Energy Transfer (DET). In those cases, the voltage is not the one for optimal generation, it is set by the electrical system, usually the battery. As can be seen in Figure 1, in the case of a constant voltage, especially if it is high, temperature increases can lead to drastic reductions in power production (that is, in the efficiency of the solar panel). If a non-linear relationship among efficiency and temperature is considered, the correct way to obtain the efficiency of a panel would be to calculate the output current of the panel at the given temperature, voltage and irradiance, and calculate the efficiency using the relationship:

$$\eta\left(T,V,G\right) = \frac{G}{V \cdot I\left(T,V,G\right)}. \tag{9}$$

Therefore, to realistically calculate the efficiency of a panel that does not operate at optimal voltage, it is necessary to obtain an expression that relates the current to the temperature and the irradiance of the panel, for any voltage conditions. Moreover, this expression should ideally be obtained only using the parameters provided by the manufacturer (α_{Isc}, α_{Imp}, α_{Voc} and α_{Vmp}), or others easily inferred from them (I_{mp}, V_{mp}, I_{sc} and V_{oc}; Equations (4) to (7). This relationship is the one that will be studied in the next section.

III. Solar panel electrical modeling

In this section, different models for modeling the currents of the solar panels are discussed. The most popular methodology for photovoltaic systems modeling is the 1-Diode/2-Resistor equivalent circuit model (see Figure 2). This method is taken as the reference result for the results of this work. However, its implementation in thermal analysis can be quite challenging, as it is represented by an implicit equation that has to be solved in each step. There are alternatives to implement this model explicitly, based on the Lambert Function and its approximations (see Appendix). Even so, it has implementation difficulties in thermal software, due to having figures of very different orders of magnitude and high precision needs. Other explicit models are analyzed as alternatives and compared between them. The explicit models analyzed where developed by Pindado and Cubas, Kalmarkar and Haneefa, and Das.

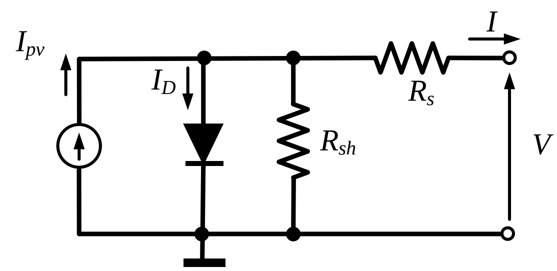


Figure 2 1-Diode/2-Resistor equivalent circuit.

It is important to stress that all the selected models can be derived from the manufacturer data. In particular, they use the three characteristic points of the *I-V* curve: short circuit (I_{sc}), maximum power point (I_{mp} and V_{mp}), and open circuit (V_{oc}), that can be obtained from Equations (4) to (7).

A. The 1-Diode/2-Resistor equivalent circuit model

The performance of a solar panel is generally modeled by using a 1-Diode/2-Resistor equivalent circuit. The equation that defines this performance (that is, the relationship among the output current and the output voltage), can be defined as[11]:

$$I = I_{pv} - I_D - \frac{V + IR_s}{R_{sh}} = I_{pv} - I_0\left[\exp\left(\frac{V + IR_s}{aV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}, \tag{10}$$

where I is the output current, V is the output voltage, R_s and R_{sh} are the series and shunt resistors, I_{pv} is the photocurrent delivered by the current source, I_0 is the saturation current of the diode, a is the ideality factor of the diode, and $V_T = nkT/q$ is the thermal voltage, n being the number of series-connected cells of the photovoltaic device, k the Boltzmann constant, T the temperature of the solar cells and q the charge of the electron. A problem with this model is that Equation (10) is not explicit. So, although we have all the parameters, it will be necessary to solve it by iterating at each step, which will slow down the thermal analysis. One way to avoid this is to make Equation (10) explicit using the positive branch of the Lambert function, W_0 (see Appendix), by using the following equation[12]:

$$I = \frac{R_{sh}\left(I_{pv} + I_0\right) - V}{R_s + R_{sh}} - \frac{aV_T}{R_s} W_0\left(\frac{R_s R_{sh} I_0}{aV_T\left(R_s + R_{sh}\right)} \exp\left(\frac{R_{sh}\left(R_s I_{pv} + R_s I_0 + V\right)}{aV_T\left(R_s + R_{sh}\right)}\right)\right). \tag{11}$$

The Lambert equation is not usually included in thermal software; therefore, the appendix shows a simple way to approximate it. The above explicit equation represents the *I-V* curve of a solar panel that is defined for a certain solar irradiance, G, and a certain temperature, T. Besides, this is a 5-variable problem that needs to be solved for each pair of environmental conditions before implementing the model. There are many methods to obtain the parameters using experimental data, but for a preliminary thermal analysis, the ideal solution is to obtain them from easily accessible data, like the datasheet provided by the manufacturer.

The current and voltage values at the three characteristic points of the *I-V* curve, short circuit (I_{sc}), maximum power (I_{mp} and V_{mp}), and open circuit (V_{oc}), allow to derive four equations to extract the values of four of the parameters. These four parameters are calculated in relation to the fifth one, the ideality factor a, and the aforementioned values of current and voltage at the three characteristic points[11,13]:

$$\frac{aV_T V_{mp}\left(2I_{mp}-I_{sc}\right)}{\left(V_{mp}I_{sc}+V_{oc}\left(I_{mp}-I_{sc}\right)\right)\left(V_{mp}-I_{mp}R_s\right)-aV_T\left(V_{mp}I_{sc}-V_{oc}I_{mp}\right)}=\exp\left(\frac{V_{mp}+I_{mp}R_s-V_{oc}}{aV_T}\right), \tag{12}$$

$$R_{sh}=\frac{\left(V_{mp}-I_{mp}R_s\right)\left(V_{mp}-R_s\left(I_{sc}-I_{mp}\right)-aV_T\right)}{\left(V_{mp}-I_{mp}R_s\right)\left(I_{sc}-I_{mp}\right)-aV_T I_{mp}}, \tag{13}$$

$$I_0=\frac{\left(R_{sh}+R_s\right)I_{sc}-V_{oc}}{R_{sh}\exp\left(\frac{V_{oc}}{aV_T}\right)}, \tag{14}$$

$$I_{pv}=\frac{R_{sh}+R_s}{R_{sh}}I_{sc}. \tag{15}$$

Equation (12) is an implicit expression for R_s. However, it also can be made explicit using the Lambert function, this time the negative branch, W_{-1} (see Appendix) and its polynomial approach. With it, the value of R_s can be then obtained from the following equations:

$$R_s=A\left(W_{-1}\left(B\exp\left(C\right)\right)-\left(D+C\right)\right), \tag{16}$$

where:

$$A=\frac{aV_T}{I_{mp}},\ B=-\frac{V_{mp}\left(2I_{mp}-I_{sc}\right)}{V_{mp}I_{sc}+V_{oc}\left(I_{mp}-I_{sc}\right)},\ C=-\frac{2V_{mp}-V_{oc}}{aV_T}+\frac{V_{mp}I_{sc}-V_{oc}I_{mp}}{V_{mp}I_{sc}+V_{oc}\left(I_{mp}-I_{sc}\right)},\ \text{and}\ D=\frac{V_{mp}-V_{oc}}{aV_T}. \tag{17}$$

Finally, to solve the model, it is necessary to give a value to parameter a. In the absence of more information or experimental results this value can be assumed to be around 1.2 or 1.3 [10,14]. This assumption can lead to negative values in the resistances of the model which lacks physical significance. Nevertheless, the mathematical model is still valid. Among the problems of this method, the high number of equations to be implemented and the calculations to be performed can be emphasized. Another drawback is the use of Lambert function. This function can be approximated, as explained in the appendix. However, the approximation is carried out by sections and special care must be taken with the value and magnitude of the variables, in order to select the appropriate branch and not incur in high numerical errors.

B. Pindado and Cubas explicit model

In this model, the value of the provided current for each voltage is defined by the following equation[15,16], which depends only on parameters from the manufacturer's datasheet:

$$I=\begin{cases} I_{sc}\left[1-\left(1-\frac{I_{mp}}{I_{sc}}\right)\left(\frac{V}{V_{mp}}\right)^{\frac{I_{mp}}{I_{sc}-I_{mp}}}\right] & ;\ V\le V_{mp} \\ I_{mp}\frac{V_{mp}}{V}\left[1-\left(\frac{V-V_{mp}}{V_{oc}-V_{mp}}\right)^{\phi}\right] & ;\ V\ge V_{mp} \end{cases}, \tag{18}$$

where:

$$\phi=-\left.\frac{\partial I}{\partial V}\right|_{V=V_{oc}}\frac{V_{oc}}{I_{mp}}\left(\frac{V_{oc}}{V_{mp}}-1\right)\simeq\frac{I_{sc}}{I_{mp}}\left(\frac{I_{sc}}{I_{sc}-I_{mp}}\right)\left(\frac{V_{oc}-V_{mp}}{V_{oc}}\right). \tag{19}$$

C. Karmalkar and Haneefa explicit model

Another alternative would be to use the equation that is defined by this model[17,18]:

$$\frac{I}{I_{sc}} = 1-\left(1-\gamma\right)\left(\frac{V}{V_{oc}}\right)-\left(\frac{V}{V_{oc}}\right)^{m}, \tag{20}$$

where:

$$\alpha = \frac{V_{mp}}{V_{oc}};\ \beta = \frac{I_{mp}}{I_{sc}};\ C = \frac{1-\beta-\alpha}{2\beta-1};\ m = \frac{W_{-1}\left(-\frac{\alpha^{-1/C}\ln\left(\alpha\right)}{C}\right)}{\ln\left(\alpha\right)}+\frac{1}{C}+1 \text{ and } \gamma = \frac{2\beta-1}{\alpha^{m}\left(m-1\right)}. \tag{21}$$

D. Das explicit model

Finally, another simple model to calculate the current based on the voltage is the one proposed by Das and defined as[19]:

$$\frac{I}{I_{sc}} = \frac{1-\left(\frac{V}{V_{oc}}\right)^{k}}{1+h\left(\frac{V}{V_{oc}}\right)}, \tag{22}$$

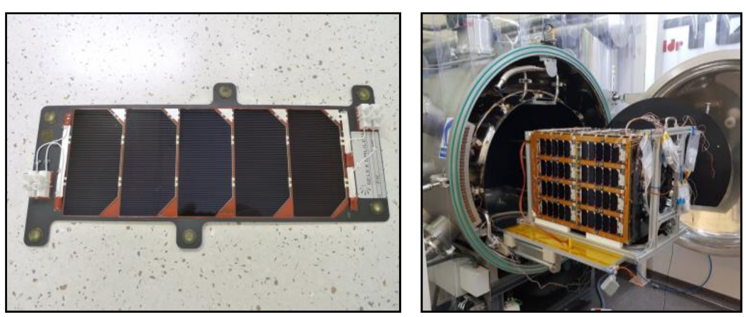
where:

$$\alpha = \frac{V_{mp}}{V_{oc}};\ \beta = \frac{I_{mp}}{I_{sc}};\ k = \frac{W_{-1}\left(\beta\ln\left(\alpha\right)\right)}{\ln\left(\alpha\right)} \text{ and } h = \frac{1}{\alpha}\left(\frac{1}{\beta}-\frac{1}{k}-1\right). \tag{23}$$

This model also needs the Lambert function approach but with fewer calculations than the equivalent circuit model. So, its implementation has been considerably simpler.

IV. Results

To show the difference between estimating panel efficiency assuming maximum efficiency and not doing so, a thermal model of the UPMSat-2 has been used. The calculation of the efficiency for non-optimal voltage has been performed using the methods proposed in the previous section. These results will allow checking if there is a high difference between using one method, another or not using any of them.



(a) (b)

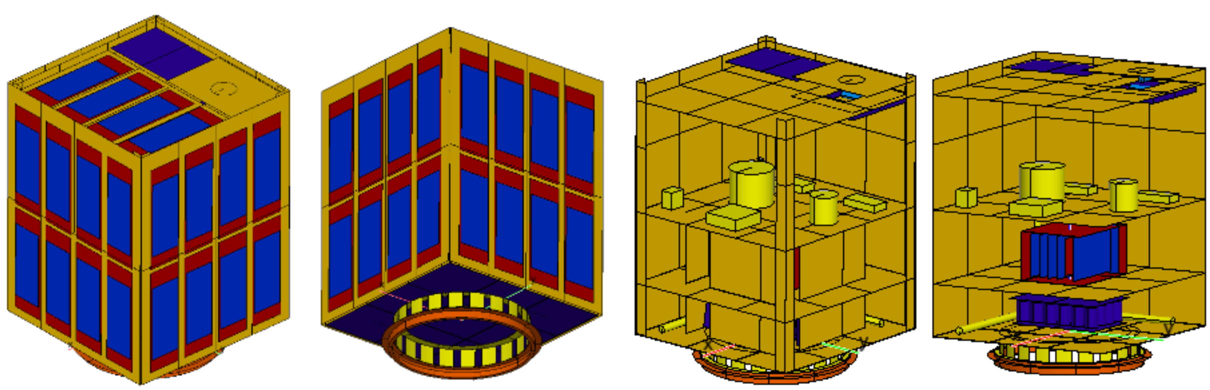
Figure 3 Selex-Galileo SPVS-5 photovoltaic modules with 5 AZUR SPACE 3G28C solar cells (a), and view of one solar panel of the UPMSat-2 satellite, composed by 8 SPVS-5 modules (b).

The UPMSat-2 satellite has five solar panels, on the side faces (+ X, -X, + Y and -Y), and on the upper one (+ Z). The solar panels of the UPMSat-2 are built on SPVS-5 modules from Selex Galileo. These modules are built with 5 Azur Space 3G28C triple junction cells from Gallium Arsenide (Ga-As) connected in series and glued to an aluminium substrate. The side panels consist of 40 solar cells (4 series of two modules each connected in series), while the upper panel consists of 20 solar cells (2 series of two modules each connected in series). For the thermal analysis, each SPVS-5 module has been taken as an independent solar item. However, a more detailed analysis should consider that for panels connected in series, the current of both will be limited by the one with the lowest operating current. It should also be taken into account that, beyond temperature and irradiance, other phenomena such as solar cell shadowing can drastically reduce the current provided by the panel and therefore its efficiency. All the necessary parameters from Equations (4) to (7) have been extracted from the manufacturer's datasheet[20] for the solar cell and are presented in Table 1. In the case of panels composed of multiple solar cells, the total voltages are obtained by multiplying by the number of cells in series, and the total currents are obtained by multiplying by the number of cell-series in parallel. As it is a panel with five cells in one series, the voltages are multiplied by five and the currents are maintained (see right column of Table 1). The value of the ideality factor has been estimated as a = 3.3. That is three times 1.1, close to the values recommended in Section II for triple junction cells when there is no information available. Note that the parameters that have been used are those of beginning of life (BOL), but depending on the duration of the mission and the amount of radiation received, it may be convenient to modify them to the extent indicated by the manufacturer.

Parameter	3G28C solar cell	Selex-Galileo SPVS-5
A_{rea} (cm^2)	30.18	150.9
α	0.91	0.91
V_{oc} (V)	2.667	13.335
I_{sc} (A)	0.506	0.506
V_{mp} (V)	2.371	11.855
I_{mp} (A)	0.487	0.487
α_{Voc} (mV/ºC)	–6.0	–30.0
α_{Isc} (mA/ºC)	0.32	0.32
α_{Vmp} (mV/ºC)	–6.1	–30.5
α_{Imp} (mA/ºC)	0.28	0.28

Table 1. Characteristic values of the AZUR SPACE triple junction 3G28C solar cell, and the Selex-Galileo SPVS 5-cell. Nominal values obtained at STC, that is AM0, G = 1367 W/m^2, and T = 28 ºC (Beginning Of Life –BOL– values)[20].

The thermal mathematical model has been built in ESATAN, which is the thermal analysis software required by the European Space Agency (ESA) in all its projects. It is a medium sized model (382 nodes) specifically built in order to suit the needs of a coupled thermal analysis with the Vega launcher thermal model from Arianespace in the frame of the Vega SSMS PoC mission launch activities. Therefore, it is the working thermal model which has been correlated with the environmental test data. The thermal model is shown in Figure 4. The two left views of the figure show the outside part of the satellite, including the solar cells. The five solar cells of the photovoltaic device have been modelled as one single node, as the solar panel surfaces are flat and made of aluminum. Therefore, the solar angle is the same for all cells in each face and the temperature of the substrate is homogeneous.



(a) **(b)**

Figure 4 UPMSat-2 thermal mathematical model, outside view (a) and inside view (b).

The considered orbit for the analysis has been the UPMSat-2 expected Sun-Synchronous Orbit, at 500 km and with an inclination of 97.4º. The attitude of the satellite is such that the +Z direction is orthogonal to the orbital plane and the +X face is permanently forming a 22º angle with the solar rays (see Figure 5).

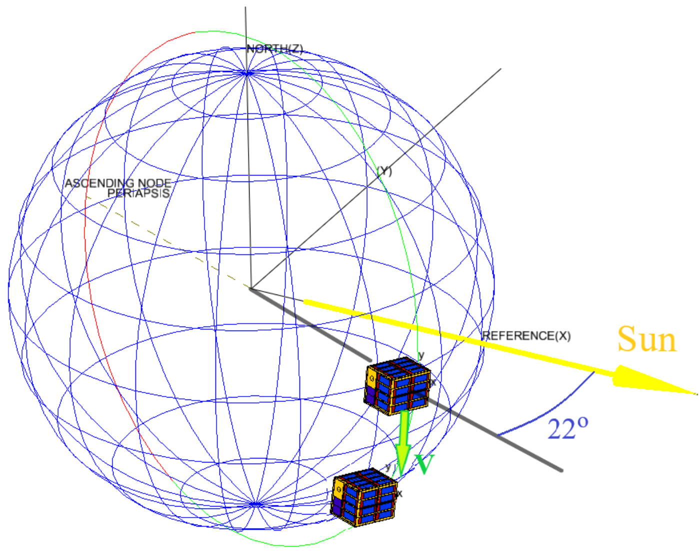


Figure 5 View of the satellite's attitude on orbit, and the Sun-Synchronous Orbit (SSO) used for the thermo-electric analysis.

The thermo-electric analysis has been performed as follows for each value of V:

- First, the radiative analysis is executed one single time, obtaining the values of Q^*_S and Q^*_A for each panel in each point of the orbit. It should be pointed out that these solar loads are obtained using a solar absorptance of $\alpha = 1$, as the value of the solar irradiance needed to obtain the solar cell parameters is the total incident solar irradiance.
- After the radiative calculation has been performed, the thermal model is solved iteratively until a periodic solution for the orbit is obtained for each value of the bus voltage, V_{bus}. For each time step in the orbit, the total solar irradiance G is obtained from the radiative analysis as $G = (Q_S + Q_A)/Area$. This value of the irradiance and the value of the temperature T obtained in the previous time step are introduced in equations (4) – (7) in order to obtain the I-V equation parameters: I_{sc}, I_{mp}, V_{mp} and V_{oc}.
- These parameters are used to obtain the value of the current, I, using any of the proposed methods. With the current, the generated power can be calculated as $P = IV$. The actual efficiency for the input parameters V, G, T is therefore obtained as per Equation (9).
- Knowing the efficiency η, the actual values of Q_S and Q_A using equations (2) and (3) are used to solve the thermal equations to obtain the temperatures for this time step. The value of the solar absorptance of the panel is provided by the manufacturer, α=0.91 (see Table 1).
- This process is repeated for each time step, and the full orbit is solved iteratively in this fashion until a periodic solution is achieved. In this solution the difference between any node temperature for any time step is below 0.01 ˚C between two consecutive orbits.

In this study, the previous method was performed for a range of voltages between 19 and 25 volts. Since the thermal analysis includes the calculation of the current, an advantage of

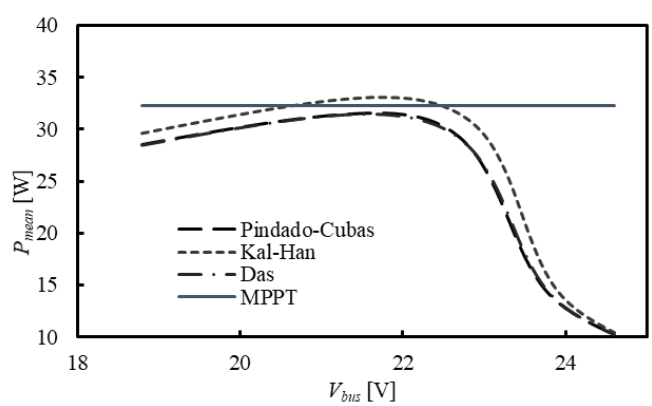
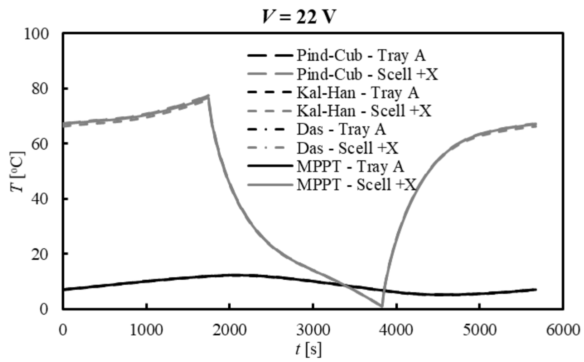


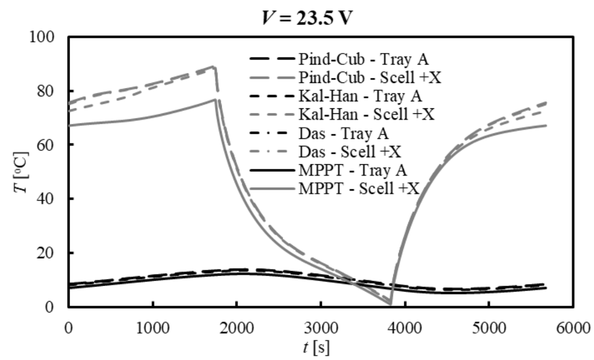
Figure 6 Average power per orbit depending on the voltage. Different types of line indicate different panel models.

the model is that it allows estimating the power produced by the panels for each voltage. This is calculated by multiplying the current of each panel by the voltage and adding all powers. Figure 6 includes the average power produced during an orbit, taking into account both the illuminated phase and the eclipse phase. This calculation has been made with the explicit methods explained above. The result that would be obtained when operating with MPPT, that is the optimum voltage for each temperature, has been marked in a continuous line.

In the mentioned figure it can be seen how assuming that the panel operates at optimal voltage is a good approximation when the voltage is close to the optimal one (21-22 V), but the power produced is overestimated when the voltage moves away, especially when it is higher. The higher the panel temperature, this overestimation will occur at lower voltages. A bad estimate of the power produced is not only a problem for the mission and for the correct design of the power subsystem; it also has an impact on the correct thermal analysis. The results of this effect are shown in Figure 7. The temperature of two nodes of the thermal model, one from the illuminated solar panel (Scell +X) and the other one from an inner tray (Tray A) of the satellite is shown in this figure. The calculations have been performed using the methods explained above to calculate the power produced by the panels. The temperature assuming MPPT is plotted with solid lines.



(a)



(b)

Figure 7: Temperature variation during one orbit for two nodes of the thermal model. Different types of line indicate different panel models. Panel operation at 22 V (a) and 23.5 V (b).

The graph on the left side of Figure 7 corresponds to 22 V operation, a voltage close to the optimum at the average temperature of the panel. In that case, there is hardly any difference between simulating with one model or another. Furthermore, the result is also almost identical to assuming that the panel always operates at optimal voltage. The graph on the right-side of Figure 7 corresponds to 23.5 V operation. At this voltage there is a significant reduction in the power produced, as can be seen in Figure 6. This leads to the panels getting much hotter than the simulation at optimal voltage presupposes. In some parts of the orbit this difference reaches 13 ºC. The internal differences are minor but not negligible, about 1-2 degrees. The different methods suggested in Section III provide slightly different results between them. However, all of them point in the same direction and away from the MPPT method.

V. Conclusions

The importance of thermo-electric modeling of the solar panels of a spacecraft is discussed in the present work. This kind of study is usually not considered due to two main reasons: 1) Firstly, it is not necessary when the voltage of the panel is controlled and always optimized. This design is usual in big satellites, but it is not always available in microsats and cubesats. 2) Secondly, the implementation of solar panels electrical modelling is complex in thermal software.

In addition, what would be the most accepted methodology to simulate the electrical behavior of the panels (the equivalent circuit model) is also discussed, a way to implement it in thermal software with only explicit equations and using information from the manufacturer being described. Three alternative explicit and simpler methods are suggested in this work. The three methods give quite similar results, the Pindado-Cubas method being the one with easiest implementation in ESATAN.

The results of this study indicate that despising the dependence of the photovoltaic efficiency on the voltage produces important variations in the estimated temperatures of solar panels. These differences are even above the margins usually used in thermal modeling. This has important implications for the satellite power generation. Besides, it can also have relevant thermal effects such as heating of adjacent areas, higher infrared emissions from the solar panel, etc. For all these reasons, it is highly recommended to include thermo-electric analysis in case of spacecraft solar panels without active control of the voltage.

Appendix I

The Lambert function, $W(z)$ is defined as:

$$z = W(z)\exp(W(z)), \tag{A1}$$

where z is a complex number. For a real variable x, the Lambert function is defined within the bracket [−1/e, ∞], having a double value for negative values of the variable x. In order to solve possible conflicts, two different branches are defined for this function, $W_0(x)$, for $W(x) \geq -1$, and $W_{-1}(x)$, for $W(x) \leq -1$. Further, the branch $W_0(x)$ is usually divided into two sections that can be better approached separately $W_0^-(x)$, for $W_0(x) \leq 0$, and $W_0^+(x)$, for $W_0(x) \geq 0$. This function represents a worthy strategy to solve some equations that involve exponentials, as if $X = Y\exp(Y)$ then $Y = W(X)$. Although the function can be written explicitly, it still needs a numerical resolution, which is reached from an approximation. A quite relevant problem is to define this approach function, which depending on the needs of precision, could be used without further calculations. After a thorough review of the literature, the following approaches of the Lambert function was found to be quite reasonable[21,22]. For the W_0^- branch:

$$W_0^-(x) = -1 + \frac{\sqrt{\varphi}}{1 + \left(\left(N_1\sqrt{\varphi}\right)/N_2 + \sqrt{\varphi}\right)}, \tag{A2}$$

where

$$\varphi = 2(1+ex),\ N_1 = \left(1 - \frac{1}{\sqrt{2}}\right)\left(N_2 + \sqrt{2}\right), \text{ and } N_2 = 3\sqrt{2} + 6 - \frac{\left(2237+1457\sqrt{2}\right)e - 4108\sqrt{2} - 5764}{\left(215+199\sqrt{2}\right)e - 430\sqrt{2} - 796}\varphi. \tag{A3}$$

For the W_0^+ branch:

$$W_0^+(x) = 1.4586887\ln\left(\frac{1.2x}{\ln\left(2.4x/\ln(1+2.4x)\right)}\right) - 0.4586887\ln\left(\frac{2x}{\ln(1+2x)}\right). \tag{A4}$$

Whereas the approach selected to solve the W_{-1} branch is[21]:

$$W_{-1}(x) = -1 - \sigma - 5.95061\left(1 - \frac{1}{1+f(\sigma)}\right), \tag{A5}$$

where:

$$f(\sigma) = \frac{0.23766\sqrt{\sigma}}{1 - 0.0042\sigma\exp\left(-0.0201\sqrt{\sigma}\right)}, \text{ and } \sigma = -1 - \ln(-x). \tag{A6}$$

Equation (A4) is especially problematic in the vicinity of $x = 0$, as it gives very high numerical errors. It is recommended then to replace with $W_0^+(x) \simeq x$ for $|x| << 1$.

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