The worst-case thermal environment parameters of small satellites based on Real-Observation Data

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The thermal environmental conditions that define the worst-case analyses of Low Earth Orbit (LEO) satellites have been selected based on the Criteria established by National Aeronautics and Space Administration (NASA) in 1994 using first Earth Radiation Budget Experiment (ERBE) data about the Radiative Energy Budget. Even if this methodology has been widely used in space missions, no review has yet been made with the new available and more precise data. Particularizing this analysis to small satellites (CubeSat, NanoSatellites, Picosatellites) the in-orbit albedo and Outgoing Longwave Radiation (OLR) variations, together with the direct Solar radiation, drive the thermal behavior of the systems. In contrast to bigger satellites, which are mainly affected by the average heat flux over their surfaces, small satellite temperatures are considerably coupled to the in-orbit variations caused by local variations in the atmosphere radiative characteristics. In order to understand all factors that take part in the thermal environment characterization of a LEO orbit, a deep study of the sampled Clouds and the Earth's Radiant Energy System (CERES) albedo and OLR time-series obtained from a satellite propagator has been performed. These time-series have been also analyzed in order to obtain the worst-case albedo and OLR profiles that maximize and minimize the temperatures in the orbit. The recommended European Space Agency (ESA) software for thermal analyses, ESATAN-TMS, is usually used for constant albedo and OLR analyses but it can be configured for allowing time-dependent profiles.

Nomenclature

A	=	area
AU	=	Astronomical Unit
C	=	thermal capacity
CERES	=	Clouds and the Earth's Radiant Energy System
COTS	=	Commercial-Off-The-Shelf
ECSS	=	European Cooperation for Space Standardization
ERBE	=	Earth Radiation Budget Experiment
ERBS	=	Earth Radiation Budget Satellite
ESA	=	European Space Agency
GMAT	=	General Mission Analysis Tool
k	=	conductive coupling
LEO	=	Low Earth Orbit
NASA	=	National Aeronautics and Space Administration
NOAA	=	National Oceanic and Atmospheric Administration
OLR	=	Outgoing Longwave Radiation

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Q	=	heat flux
r	=	radiative coupling
SBA	=	Solar Beta Angle
SZA	=	Solar Zenith Angle
T	=	temperature
α	=	Solar absorptance
ε	=	Infrared emissivity
σ	=	Stefan-Boltzmann constant

I. Introduction

During the last years, small satellites have turned into a real alternative to some of the traditional Low Earth Orbit (LEO) missions. Before this, space agencies had the monopoly of the Space exploration and exploitation. However, the increasing interest in the commercialization of big data and the globalization of the information have attracted the private investments to the so-called "New Space"[1]. This increasing demand of small satellites have resulted in an innovation process that has substantially reduced the cost of the access to Space. A great market has been built around this sector not only for providing new technology but also for technical advice, launch operation, design support, etc.

This revolutionary change in the Space industry have forced the New Space enterprises to follow new design methods which are very different from the traditionally followed by the space agencies. The Low-Cost requirements of these systems have led to the standardization of the used platforms and instrumentation (i.e. CubeSats) as well as to the development of robust designs with a wide range of applications[2].

This standardization has provided access to Space to institutions and companies with not enough resources and knowledge to design a whole satellite by their own. In this way, they can get a suitable platform for their specific application based on Commercial-Off-The-Shelf (COTS) components. Nevertheless, this lack of experience and founds drives to a design process where the system is not well enough analyzed to guarantee the success of the mission.

For many years, the traditional satellite design philosophy was dominated by a high level of confidence of the used technology and an exhaustive verification and testing process in order to guarantee the survival of the system to the harsh environment during its whole operational life. In contrast, "New Space" promises a faster, easier and cheaper design process that in many cases results in early failure mission[3]. A National Aeronautics and Space Administration (NASA) study observed that between the years of 2000 to 2016, 41.3% of all small satellites launched failed or partially failed[4]. Many studies have been carried out to come out with the reasons why there is a great infant mortality in this kind of satellites. Most of them conclude that in many case, failures could have been avoided by a more carefully design and testing at ground[5].

It is well known that in most cases, an inadequate thermal design could drive to a reduced lifetime due to several failures regarding the electronic components, the battery performance, etc. In order to get a reliable thermal design, a detailed thermal model should be configured. There is a wide range of software for space thermal analysis and modelling. Traditional satellites must be analyzed with a supported software by the corresponding space agency, but it is not the case for CubeSats and similar satellites. In some cases, own-made thermal solvers for analytical models are used for this kind of missions leading to a considerably uncertainty associated to the thermal performance in Space.

At the beginning of the thermal design process, one of the main steps is to define the thermal environmental conditions that the satellite must deal with. In order to ensure the survival of the system during its whole life the thermal design is usually based on two or more extreme cases where the hottest and coldest conditions are used. For a LEO satellite, the thermal environment is defined by three main parameters. Direct Solar radiation is usually the main heat source reaching the satellite. Its contribution is measured by the Solar Constant or Solar Irradiance that takes an average value of 1361 W/m^2 at 1 Astronomical Unit (AU). However, when orbiting the Earth in a LEO, its value is not constant during the year because the distance between the Earth and the Sun changes due to the orbit eccentricity reaching values between 1322 and 1414 W/m^2. In addition, the amount of Solar radiation reaching the satellite during an orbit also depends on the eclipse time and the angle of incidence over the satellite surfaces. Beta angle, which is the angle between the Sun direction and the orbital plane, plays an important role in the selection of the hottest and coldest orbit. The other two parameters are related to the Earth influence by the infrared emitted radiation, which is called Outgoing Longwave Radiation (OLR), and the reflected solar radiation, which is known as albedo. These two contributions are not constant during the orbit, and its variability depends on the characteristics of the surface and the atmosphere below the satellite trajectory.

Selecting the worst-case environment should not only consider the variability of the eclipse duration and the value of the Solar Irradiance, but also the albedo and OLR worst-case values[6]. These two values are partially correlated which means that they cannot be selected without considering the dependence between them. They should be selected from wide enough range of samples, which allows to consider enough situations for guaranteeing the survival of the system to its extreme temperatures. However, the planetary thermal environment is not the same for different orbits. A particularized analysis for the considered orbit is required to obtain reliable thermal worst-cases.

When facing the thermal environment characterization of a particular satellite, it is important to consider that the pair of values that would drive the system to its maximum and minimum temperatures does depend on its own characteristics. The thermo-optical properties of the external surfaces of the analyzed satellite should be considered for selecting the worst-cases parameters. Moreover, the thermal inertia of the system determines not only the orbital point where the maximum and minimum temperatures would take place but also the amplitude of the temperature response. Bigger systems thermal response would be driven by the orbital average value of albedo and OLR. In contrast, lower massive systems, with a lower associated characteristic time, would be more coupled to the variations of the thermal environment. For that reason, when analyzing a small satellite, the definition of these worst-cases become even more important.

In the past, NASA has established the criteria for the selection of the worst-case thermal environmental parameters[7]. Other space agencies, as ESA[8], recommends the use of these criteria due to its success in several missions since the nineties, but this methodology has not been reviewed in the last decades. In 1994, Anderson & Smith[9] used radiative data from one of the first available sources, the Earth Radiation Budget Experiment (ERBE). It was a multisatellite experiment consisting in the low-inclination Earth Radiation Budget Satellite (ERBS) and two National Oceanic and Atmospheric Administration (NOAA) Sun-synchronous satellites. They collected such Earth radiation budget parameters as incident and reflected sunlight and the OLR from November 1984 and July 1987. Nowadays, there is a great amount of data which can be used instead, and the status of the technology allows for a particular characterization and more complex analysis. One of these satellite-based observations databases is the Clouds and the Earth's Radiant Energy System, CERES[10]. It provides information about Earth radiative fluxes on the Top of Atmosphere among other things.

The work presented in this paper aims at showing the relevance of the worst-case thermal environment characterization in small satellites. To do so, the definition of the albedo and OLR worst-cases values is based on a new methodology[11] from particularized analysis of Real-Observation data. The main differences between the proposed criteria and the NASA traditional criteria are the following:

- The proposed worst-cases consist of single-orbit time-dependent profiles of albedo and OLR values instead the constant values used by NASA.
- The resultant temperature profile does not aim to bound the real temperature behaviour but to obtain the minimum and maximum temperatures representing the hottest and coldest orbits.
- These minimum and maximum temperatures are the result of potential peaks in the planetary heat load that can be found in the surroundings of the hottest and coldest point in the orbit.

As pointed out by the European Cooperation for Space Standardization (ECSS)[8], classically, the radiative environment for a spacecraft orbiting the Earth in a LEO, is adequately represented by assuming constant values of albedo coefficient and OLR. However, these assumptions are not valid for some cases such as polar orbits around Earth where albedo reflectivity can increase around the polar ice caps and external equipment with low thermal inertia that can be sensitive to infrared fluxes and albedo variation. This phenomenon can be also relevant in small satellites, because they are considerably coupled to the thermal environmental variations.

The content of this paper is organized as follows. Firstly, the proposed methodology is explained step by step in Section II, from the worst-case orbit selection to the setting of the thermal analysis with ESATAN-TMS, the supported software of the European Space Agency. Secondly, a complete selection process is shown and compared to NASA selection criteria in Section III and IV. Finally, the proposed thermal environmental worst-cases are used for the analysis of a simple model representing a small satellite in Section V. Conclusions are drawn in Section VI.

II. Proposed Methodology

The worst-case selection process should start with an analysis of the real behavior of the system in the corresponding orbit. By doing so, the long period temperature variations can be identified, which depend on the beta angle. Traditionally, the worst-case orbit selection was based on the eclipse duration given by the beta angle. Long eclipses corresponded to the cold worst-cases, and short or inexistent eclipses were associated to the hot worst-cases. However, this decision is made without considering the effect of the planetary thermal environment. Although the orbital average heat load is usually driven by Solar heat load, the temperature of systems with a low characteristic time is driven by the instantaneous heat flux, which could reach a maximum independently of the eclipse duration. For that reason, it is important to consider not only the albedo and OLR heat load but also the characteristics of the system when selecting the worst-cases orbits.

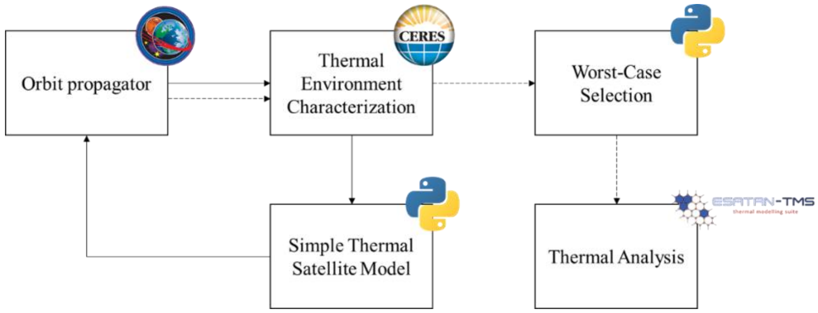


Figure 1. Scheme of the process-flow folowed for selecting and analysing the worst-case profiles.

The process followed by the methodology used corresponds to the closed loop shown in Figure 1. First, the orbit is configured in an orbit simulator such as GMAT (General Mission Analysis Tool). Once propagated the orbit, the corresponding albedo and OLR values at each time step are obtained from CERES data (2018)[12]. These data are structured in global matrices with spatial resolutions of 1º x 1º and hourly temporary resolution. Although the time step of the propagation should be small enough for considering every potential peak in the planetary heat flux, the hourly temporary resolution of CERES is quite enough for showing the atmosphere variations that could affect the thermal behavior of the satellite. An example of used data is shown in Figure 2.

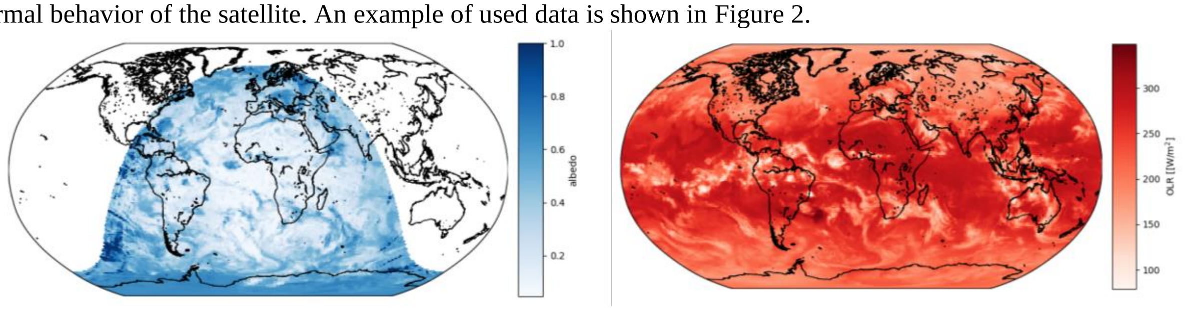


Figure 2. CERES global map of albedo (left blue), OLR (right red) corresponding to the 12:00 h UTC of 1st Jan 2018.

After the Thermal Environment characterization by interpolation in the albedo and OLR matrices, a simple thermal satellite model is used to simulate the thermal behavior during a whole year. By doing so, the relationship between the maximum and minimum temperatures with regard to the beta angle can be obtained and the worst-case orbit can be identified. The complexity of the used model is a choice of the thermal engineer that should be selected considering not only the approach to the real design but also the required computational weight of the model. Here, a simple spherical satellite is considered to allow for a complete year temperature simulation. Its transient behavior is given by

$$C_s \dot{T}_s = \dot{Q}_{si} + \dot{Q}_{ss} + \dot{Q}_{sa} + \dot{Q}_{sp} - \varepsilon_s A_s \sigma T_s^4 \qquad (1)$$

where C_s is the system thermal capacity, Q_{si} is the internal heat flux; Q_{ss}, the Direct Solar heat flux; Q_{sa} the albedo heat flux; and Q_{sp} is the IR planetary heat flux (so called OLR). The last term is the radiative dissipated heat flux, where ε_s is the IR emissivity; A_s the system external area; σ, the Stefan-Boltzmann constant and T_s the system temperature.

Following the same approach as C.G. Justus et al.[7] the characteristic time of the system, t_s, which drives the temperature response rate, can be obtained from Equation 1,

$$t_s = \frac{C_s}{4\varepsilon_s A_s \sigma \overline{T}_s^3} \tag{2}$$

where T_s the average orbital temperature.

The analysis of this expression shows the main parameters that have an influence in the temperature response of the analyzed spacecraft. The lower the characteristic time, the faster the temperature response, and therefore the faster the system reaches the thermal equilibrium. Considering 0.8 and 800 W/kg K as typical values of emissivity and specific thermal capacity respectively, the characteristic time of the system is directly associated to the mass to area ratio. During the last years, the design trend has evolved to the miniaturization of the electronics getting systems even smaller than the well-known CubeSats as shown in Figure 3. The State-Of-Art of the Small Spacecraft Technology has been updated by NASA[13].

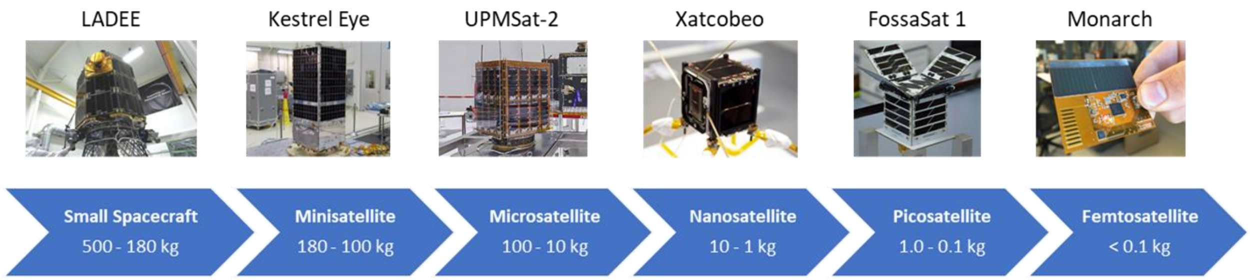


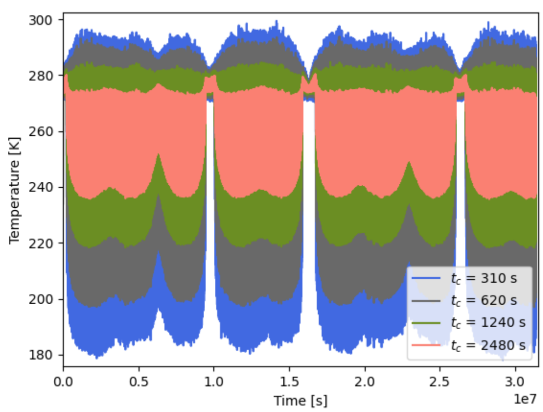
Figure 3. Miniaturization process in the space system designs.

Knowing the thermal environment that our spherical spacecraft is exposed to, the temperature response can be evaluated based on different characteristic times. The selection criterion is applied to an orbit and a satellite example. Their characteristics are shown in Table 1.

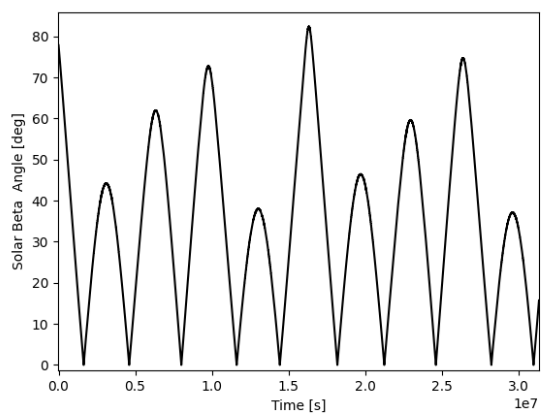
Table 1. Orbit and satellite characteristics for the beta angle worst-case selection.

Orbit characteristics		**Spherical satellite characteristics**	
Start date	01/01/2018 00:00	**Radius, *r***	0.1 m
Semimajor axis, *a*	6945 km	**View Factor, F_{SP}**	0.3
Eccentricity, *e*	0.0º	**Absorptance, *α***	0.64
Inclination, *i*	60.0º	**Emissivity, *ε***	0.85
Raan, *Ω*	0.0º		
True Anomaly, *ν*	0.0º		
Period	5765 s		

As shown in Figure 4, maximum and minimum temperatures have different absolute values, and very different trends appear. The dependence between the temperature response and the Solar Beta Angle (SBA) can be appreciated. In addition, a considerable change is observed for the range of SBA where the eclipse disappears.



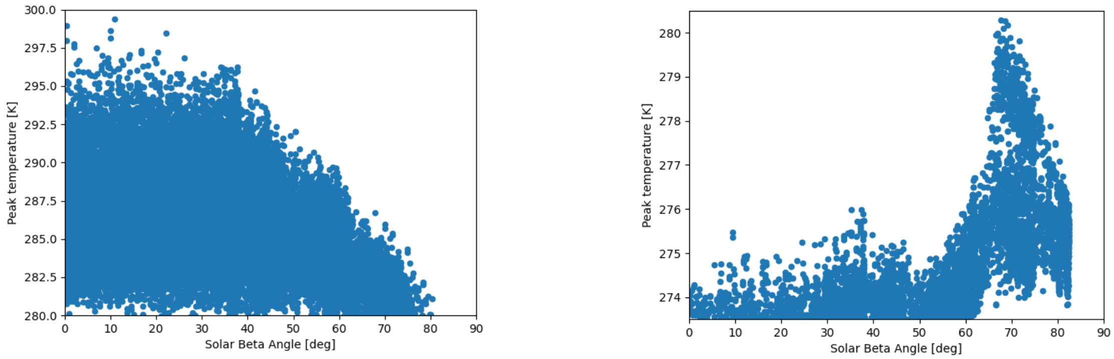
a)



b)

Figure 4. a) Temperature and b) SBA evolution for the considered orbit during a whole year.

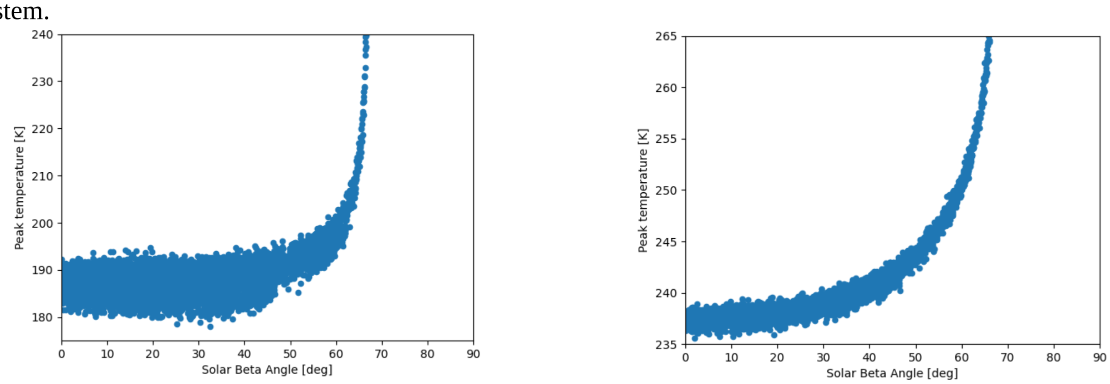
In order to select the hottest and coldest orbit, an analysis of the maximum and minimum values as a function of the Solar Beta Angle should be performed. As can be observed in Figure 4, maximum temperatures are obtained for different orbits depending on the characteristic times. While the satellite with the higher characteristic time reaches the maximum temperature for the orbit with null eclipse time, the other systems reach a maximum for the orbits where the instantaneous heat flux also reaches its highest value. The temperature of the highest peaks with regard to the Solar Beta Angle are shown in Figure 5, for the lowest (310 s) and higher (2480 s) characteristic times considered in Figure 4. A very different trend is observed in each case reaching the maximum temperatures for around 0º and 70º, respectively.



a) **b)**

Figure 5. a) Maximum peak temperatures for the a) lowest (310 s) and b) highest (2480 s) characteristic time as a function of the SBA.

Analyzing the SBA corresponding to the lowest negative peaks, the distributions shown in Figure 6 are obtained. In this case, it can be observed how the system with the higher characteristic time reaches its minimum temperature for the minimum SBA where the eclipse is a maximum. In contrast, for the lowest characteristic time system, the minimum temperature does not really present a dependence with the SBA up to the moment that the eclipse disappears. The criteria should be based on the eclipse duration instead, giving more relevance to the lowest total heat load over the system.



a) **b)**

Figure 6. a) Minimum peak temperatures for the a) lowest (310 s) and b) highest (2480 s) characteristic time as a function of the SBA.

Once selected the hottest and coldest orbits, it is possible to increase the amount of data corresponding to the selected orbits by the propagation of a whole year with a constant SBA. By doing so, the effect of the SBA can be decoupled and the potential variations along the epoch can be considered. The resulting albedo and OLR profiles for the selected orbits have a seasonal behavior every orbit during the year. For that reason, it is possible to extract the seasonal component and focus the analysis only in the potential peaks that could drive the system to its maximum and minimum temperatures. When selecting these values, it is important to bear in mind that the albedo coefficient and the OLR are partially correlated and therefore, they cannot be analyzed independently. In addition, as pointed out by

Anderson & Smith[9], albedo coefficient also depends on the Solar Zenith Angle (SZA) and its variability around the orbit mainly depend on it, reaching its higher values for SZA near 90º, which occur at the entry and exit points of the eclipse.

In order to select these potential peaks that would drive the system to its maximum and minimum temperatures, it is required to find its location in the orbit. Systems with lower thermal inertia are more coupled to the peak variations and their maximum and minimum temperatures used to be paired to the heat flux profile. In contrast, systems with higher thermal inertia reach their extreme temperatures at the end of the illumination period (hottest) and at the end of the eclipse (coldest).

The result of this worst-case selection is an albedo and a OLR profile based on the seasonal behavior with a peak applied at the corresponding location to obtain the maximum and minimum temperatures. Although the thermal analysis software allows for constant thermal environment characteristics as provided by NASA, in order to evaluate the temperature response under the profiles obtained, it is required to perform analyses with variable albedo coefficient and Earth temperature.

Comparing the methodology proposed here with the NASA selection criterion, a closer behavior to the real temperature profile is obtained, together with the maximum and minimum temperatures in the hot and cold case orbit, respectively. However, while NASA methodology provides the hottest and coldest limit for the whole orbit, the one proposed here just provides a limit at the maximum and minimum temperatures location. In addition, a particularized analysis of the worst-case orbits provides a closer environment than the NASA selection criteria, which is standardized for a range of orbits.

III. Hot and Cold Orbit Selection

At the beginning of the spacecraft design process, a rough characterization of the space thermal environment is enough to study the feasibility of the mission. Once the detailed design process starts, it is required to perform a deep study about the worst-case environments the satellite must survived to. Knowing the potential orbit parameters, the temperature response of a reduced model can be obtained by taking into account the real thermal environment variations during its trajectory. In this case, the satellite and orbit characteristics shown in Table 1 have been considered for the analysis.

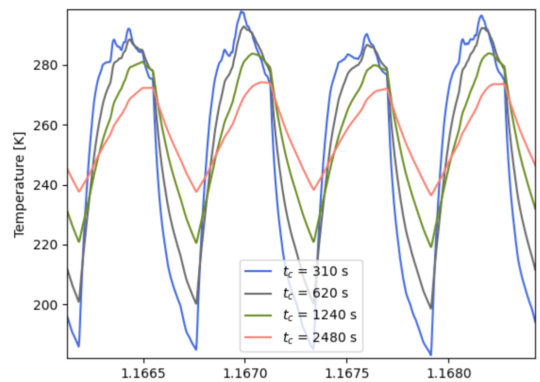


Figure 7. Detailed temperature response for 4 periods and different characteristic times.

Based on the previously explained thermal model, the temperature response shown in Figure 7 can be obtained. It can be observed how the system with the lowest characteristic time follows the thermal environment variations showing a higher temperature range and several prominences due to the heat flux peaks. Analyzing its maximum and minimum temperatures for a whole year similarly as done in Figure 5 and Figure 6, it can be determined that the SBA that maximizes and minimizes its temperature is 0º in both cases. In addition, from an iterative study of the detailed temperature response, the maximum and minimum temperature locations can be obtained.

As pointed out before, it is possible to propagate the defined orbit keeping a constant SBA by applying two maneuvers per orbit[11]. A considerably greater amount of data focused on the worst-case orbit is obtained where the epoch influence can be evaluated. Nevertheless, the main change in the thermal environment during the year is associated to the direct Solar radiation and the Solar Irradiance, which takes values between 1320 and 1412 W/m^2. In the following analysis, this effect is decoupled from the thermal environment characterization, but when defining the worst-case parameters, minimum and maximum values of the Solar Irradiance must be used for the coldest and hottest worst cases, respectively.

IV. Planetary Thermal Environment Characterization

When selecting the albedo and OLR that maximizes and minimizes the temperatures of the studied system, not only its mass and the outer area should be considered. The thermo-optical properties as well as the geometry of the spacecraft are two important parameters that weight the influence of the albedo and the OLR. A system with a high absorptance and a low emissivity would be more sensitive to the albedo variations, while the temperature of a system with high emissivity and low absorptance would be driven by the OLR. In addition, the geometry and the orientation of the spacecraft could affect the worst-case values due to the potential reflections over the satellite surfaces or even due to hidden parts that would not be exposed to part of the external heat loads. In this case, the geometry influence has been neglected considering a spherical satellite. However, using a more detailed thermal model, this effect could be considered.

In this section, the worst-case thermal environmental conditions would be selected for two particular cases through the NASA selection criteria and the time-dependent proposed criteria. Then, a comparison between them would be performed based on the temperature response of the system in both cases.

NASA Criteria

In 1994, NASA established a criterion for the worst-case environmental conditions selection based on data retrieved from ERBE, which is a multisatellite experiment composed of the low-inclination ERBS and two NOAA Sun-synchronous satellites. This criterion was based not only in the orbit characteristics but also in the satellite properties. The data treatment performed was based on averaging the values of albedo and OLR along the satellite trajectory in different situations. This average time is directly related to the time constant of the system by a way that the appropriate average time to be used should be between a fourth and the value of the system time constant. The values obtained are then treated as a 2D distribution where the correlation between the albedo coefficient and the OLR can be appreciated. A correction is made to eliminate the SZA dependence from the albedo data. Once the orbital beta angle is selected, the corresponding albedo value should be corrected with the average SZA during the orbit. In addition, a distinction is made as a function of the orbit inclination providing three ranges: 0º to 30º, 30º to 60º and 60º to 110º. This is because the albedo and OLR dependence with the Earth latitudes as pointed out by González-Bárcena et al[11]. While lower inclination orbits would have a reduced range of latitudes, higher inclination orbits would practically pass through the entire range of latitudes.

In order to consider the influence of the thermo-optical properties, NASA[6] provides three potential cases which have been obtained based on statistics. For the Hot worst-case, maximum albedo, maximum OLR and a combined case is provided for a critical analysis, where a 99.9% of the cases are considered, or for a non-critical case where only the 95% of the albedo and OLR values would be represented. The Cold worst-case present other three cases based on the selection criteria of minimum albedo, minimum OLR, and a combined case.

For this study case, considering characteristic times around 300 s and 1100 s, the 128 s average time case seems to be the closest one according to the NASA established criteria for the lowest value, while the 896 s average time should be used for the highest value. Regarding the inclination range selection, the 60 º inclination orbits are included in two ranges. Comparing the provided values for both ranges, the more restrictive case is considered (60º to 110º). These worst-case values are shown in Table 2. Due to the SZA correction, an additional term of 0.05 must be added to the albedo coefficient shown.

Table 2. NASA albedo and OLR worst-case values for the considered orbit and satellite characteristics[6].

	Worst-Case	128 s		896 s	
		Albedo [-]	**OLR [W/m²]**	**Albedo [-]**	**OLR [W/m²]**
HOT	**Alb**	0.50	180	0.35	202
	Comb	0.31	262	0.28	259
	OLR	0.22	331	0.20	294
COLD	**Alb**	0.06	273	0.09	264
	Comb	0.16	212	0.17	218
	OLR	0.38	111	0.33	148

Time-dependent Criteria

The proposed criterion is based on a particular study of the conditions for a fixed Solar Beta Angle. Even though not every orbit pass through the same trace, albedo and OLR profiles have the same shape. Therefore, it is possible to decompose the orbit profiles in three main components: trend, seasonality and residuals. Trend values change from one orbit to each other while the seasonal component remains for the considered SBA. On one hand, the worst-case selection consists of the evaluation of the trend component to find the values that make the system reach their extreme temperatures. On the other hand, the residuals should be studied as potential deviation from the seasonal component.

The study of the residuals must be performed for the orbit location where the maximum and minimum temperatures take place. This is because the main objective is to find which peak would lead the system to its extreme temperatures but keeping the shape of the temperature profile. In order to do so, the temperature deviation from the mean considering only the residuals contribution is evaluated providing the value of the albedo and OLR in the peak and the corresponding temperature deviation. A step function with an equivalent heat flux and the required duration to reach the temperature step is calculated at the corresponding location in the orbit.

The resulting albedo and OLR profiles for the hottest and coldest cases of characteristics times of 300 s and 1100 s are shown in Figure 8. In this case, both extreme temperatures are obtained for SBA = 0º. For the lowest characteristic time, maximum temperatures are obtained near the minimum SZA location, while for the higher characteristic time, this maximum has a delay in time. In contrast, minimum temperatures in both cases coincide at the end of the eclipse. As pointed out previously, the equivalent albedo and OLR peaks should be located in these points for evaluating the worst cases.

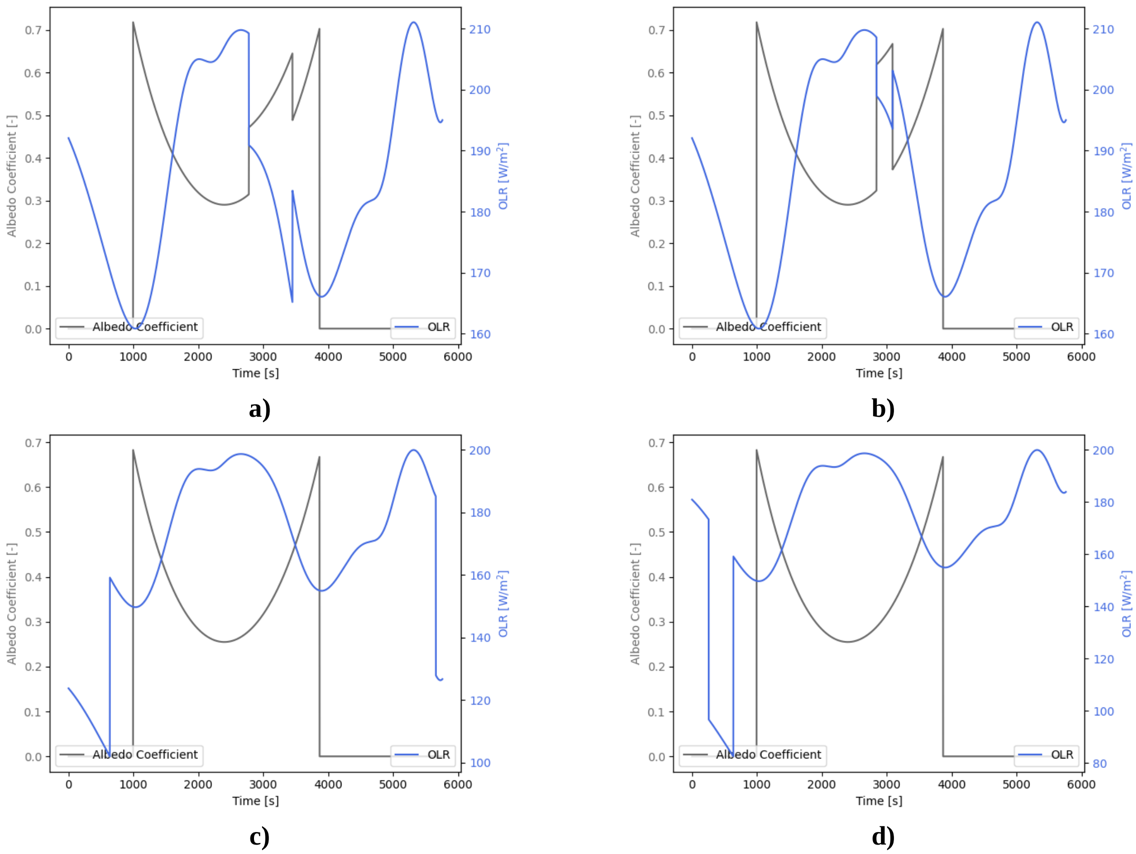


Figure 8. Albedo and OLR profiles for the a) coldest and b) hottest worst-cases of the t_c = 300 s and c) coldest and d) hottest worst-cases of the t_c = 1100 s.

V. Real application in ESATAN-TMS

In order to check the influence of both methodologies, a thermal analysis of a simple model have been performed with ESATAN-TMS, which is a complete thermal modelling environment allowing for radiative and thermal analysis. The proposed model is based on the work developed by Perez Grande et all[14] consisting in a first node representing the external faces of the small satellite, which consists on the solar panels and its support (SP); and a second node representing the internal structure (PL). In this paper, the external node is called by the subindex "*e*" and the internal node is named as "*i*". While the IR planetary, Q_e, albedo, Q_a, and solar heat flux, Q_s, are reaching the external node, the internal node would be exposed to the internal heat dissipation, Q_i, as well as the radiative and conductive flux coming from the solar panels. These two contributions depend on the conductive and radiative coupling, which are represented by k_{ie} and r_{ie}, respectively. In addition, each node is represented by its thermal capacity C, its surface area, A and its thermo-optical properties, ε (emissivity) and α, (absorptance).

Analyzing the whole system as a unique node, the ratio mass to area drives the thermal response of the system through the definition of the characteristic time. However, if the external structure of the satellite is thermally decoupled from the internal payload, the characteristic times should be independently considered. Even though the payload would not be sensitive to rapid changes in the thermal environment, the external structure's extreme temperatures are. In order to illustrate this behavior and the relationship with regard the thermal environment, a satellite with the following characteristics would be analyzed.

As pointed out before, low characteristics times would be more sensitive to the thermal environmental variations. Solar panels designs are becoming a trade-off solution between structural resistance and low mass. Keeping the area as a constant, reducing mass would reduce the characteristic time. A honeycomb solar panel structure with two skin of carbon fiber reinforced polymer with a thickness of 0.1 mm each one and 5056 aluminum alloy core with thickness 9.35 mm would be considered. The solar cell assembly is composed by fused silica coverglass (Corning 7940) with a thickness of 0.325 mm and 0.15 mm of photovoltaic cell thickness. The solar cells efficiency depends on the temperature but for this preliminary analysis, and average value of η = 0.3 is considered. A unique thermo-optical property corresponding to the Solar Cells is used for the outer surfaces (α = 0.92[1 - η], ε = 0.85) while the inner surface of the Solar Panel support is Iridite 14-2 (α = 0.08, ε = 0.15). The internal structure would be modelled as a 2 mm thickness cube of Aluminum 7075-T7351 with Iridite 14-2 in the outer surface.

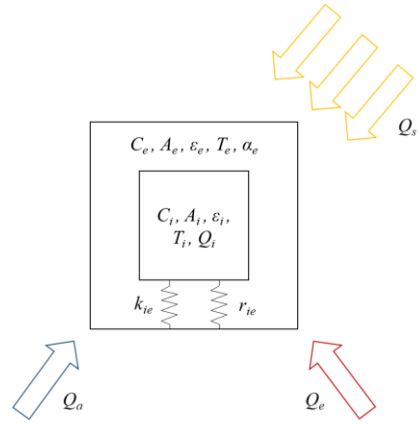


Figure 9. Scheme of the thermal model used in ESATAN-TMS.

Two cases are considered to illustrate the different thermal environments to be used depending on the characteristic time of the system. The only difference between them is the conductive coupling, k_{ie}, used in the cases analyzed.

1. The solar panel support is considered to be attached to the structure through four unions with a conductive coupling of 0.021 W/K each one. In addition, the radiative coupling between the external and internal node results 0.034 W/K^4. Considering an orbital average temperature of 270 K, the characteristic time to be used in the thermal environment selection criteria is around 300 s.
2. The solar panel support and the internal structure are considerably coupled presenting a similar behavior in the temperature response. Both nodes would behave as a single node with the thermal capacity resulting from the sum of their corresponding values. Considering also an orbital average temperature of 270 K, in this case, the characteristic time to be used increases up to 1100 s.

This thermal model is analyzed for the orbital parameters previously established in Table 1 for the worst-case Solar Beta Angle. ESATAN-TMS provides the results of the radiative problem in order to find the cyclic solution of the thermal problem using the albedo and OLR values shown in Section IV. The software uses a Crank-Nicholson method to solve the following Ordinary Differential Equation System,

$$\begin{cases} C_e\dot{T}_e = \dot{Q}_e + \dot{Q}_s + \dot{Q}_a + k_{ei}(T_i - T_e) + r_{ei}(T_i^4 - T_e^4) - \varepsilon_e A_e \sigma T_e^4 \\ C_i\dot{T}_i = \dot{Q}_i - k_{ei}(T_i - T_e) - r_{ei}(T_i^4 - T_e^4) \end{cases} \quad (3)$$

A. Case 1

The analysis of the thermal model considering a low conductive coupling (Figure 10) shows a different behavior for the external and internal node. Firstly, it is important to understand the behavior of the external node with respect to the external flux. For the hot worst-case, NASA maximum albedo values provides the maximum temperatures. As the absorptance of the system is around 0.64, the albedo heat flux reaches a considerable importance with respect to the OLR. For that reason, such high albedo value provides a closer temperature range to the time-dependent methodology. However, considering a constant value for the albedo makes that the worst-case temperature profile overestimates (around 10 ºC) the temperature response during the range 2000 to 3000 s, if compared to the temperature response of the orbit that would provide the maximum temperature through the proposed methodology.

Focusing on the minimum temperatures provided by cold worst-cases, a different behavior is observed between both methodologies. As previously explained, time-dependent criterion bases the worst-case selection in the study of the potential peaks that could make the system to drive out of the seasonal shape. The minimum absolute value reached by both criteria is almost the same. However, a difference of about 5 ºC is observed during the most part of the eclipse. NASA worst-case corresponds to the minimum OLR (with a high albedo value associated). Analyzing the evolution of the internal node temperature, it can be observed that the maximum and minimum temperatures obtained for the hot and cold worst-cases, respectively, are different for the NASA and the time-dependent criteria. These differences are greater than the ones obtained for the external node because the internal node are more coupled to the average heat flux coming from the solar panels, which has more extreme values in the NASA worst-cases.

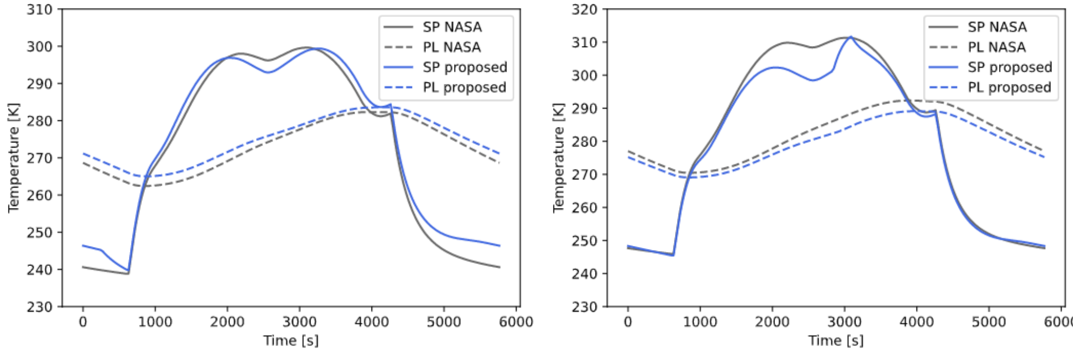


Figure 10. Case 1 (decoupled nodes) thermal model temperature response for the coldest (left) and hottest (right) worst-cases using NASA and time-dependent proposed criteria.

Let us think about a system with an external surface with thermo-optical properties of high emissivity and low absorptance. In this case, it is appropriate to think that the worst-case of NASA potential cases would be the maximum OLR with a low associated albedo coefficient value. If this case is compared to the time-dependent worst-case profiles, a wider difference would be obtained between both methodologies. This is because the high OLR value would neglect the orbital variations and the albedo value would underestimate the differences between the illumination and the eclipse periods given a reduce range of temperatures than the real behavior[11].

B. Case 2

When increasing enough the thermal coupling between the external and the internal node, their temperature behavior would be as close as considering a unique node with the total thermal capacity. The results of this analysis are shown in Figure 11 for the cold and hot worst cases, respectively. If comparing them with the decoupled analysis, a narrower range is observed as well as a smoother behavior. If the analysis is focused on the differences between NASA and the proposed methodology, a very similar temperature response with the same minimum temperature is obtained for the minimum OLR NASA cold worst-case. However, for the hot extreme case the differences with regard to NASA worst-case are greater. This is because NASA establishes that the pair of values to be used correspond to the ones that provide the maximum temperatures in the system. While maximum albedo case fitted the proposed temperature range closer than the combined case, this provides a slightly greater maximum temperature.

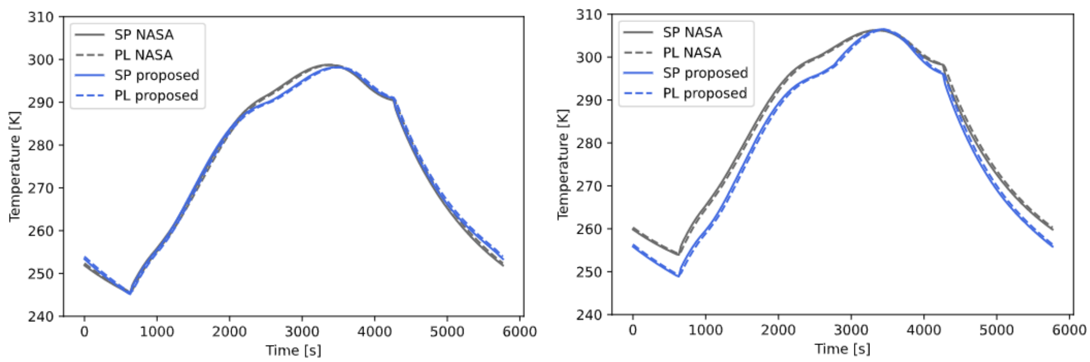


Figure 11. Case 2 (coupled nodes) thermal model temperature response for the coldest (left) and hottest (right) worst-cases using NASA and time-dependent criteria.

VI. Conclusion

When studying the thermal environment in Low Earth Orbits, it is important to consider not only the Solar heat flux but also the albedo and the OLR. In some cases, the worst-case orbit, which is defined by the Solar Beta Angle, is selected based on the eclipse duration. However, this is only valid for big satellites with high characteristic times. Smaller satellites are usually coupled to the heat flux variations that reach a peak when the sum of the solar, the albedo and the OLR heat flux is maximum.

The work presented in this paper aim at proposing an alternative criterion to select the worst-case environmental parameters for LEO satellites thermal analysis. The use of time-dependent profiles provides a more realistic environment also reaching the maximum and minimum temperatures in the orbit. Compared with NASA selection criteria and depending on the characteristics of the analyzed system, it has several advantages and disadvantages.

As shown in Section V, differences between both methodologies become smaller for systems with high characteristic times. This is because they are more coupled to the average heat flux during the orbit which can be well modelled by constant values of albedo coefficient and OLR. However, differences may be greater depending on the selected NASA worst-case, considering the system thermo-optical properties. A particularized analysis of the selected orbit thermal environment could reduce these differences.

When the system, or a part of it, has a low characteristic time, orbital variations of the albedo coefficient and the OLR could make the NASA criteria to differs from the real behavior giving an oversized thermal environment. Although it provides the upper and lower limits of the temperature during the whole period, these bounds could have considerable differences with respect to the real temperature response. These differences are reduced by using the time-dependent criteria which is based on the study of the albedo and OLR mean deviations.

Finally, let us think about a real satellite where there would be different systems in the outer surface with different thermo-optical properties (cameras, antennas, sensors, solar panels, etc.), which are exposed to the planetary thermal environment. There would not be possible to select a common pair of values of albedo and OLR from the potential NASA worst-cases, which maximizes and minimized the temperature of every system. Using the time-dependent profile, a unique worst-case neither would be possible, but differences would be reduced through the use of the seasonal component.

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