

ENVIRONMENTAL THERMAL LOADS INCIDENT ON THE SATELLITES OF THE BRAZILIAN SPACE PROGRAM

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Abstract

The satellite thermal control is an energy management process in which the environmental heating plays a major role. A body in space is submitted to different radiations and the direct solar radiation is that one what more affects its temperature, but the albedo (Earth reflected sunlight radiation) and the Earth IR (Infrared radiation) emitted energy also must to be take in account. This paper presents the algorithm of a computational code for determination of the incident external thermal loads on the satellites, developed at the Brazilian National Space Research Institute (INPE), and that has been used successful in the all thermal analysis of the Brazilian Space Program satellites. The obtained temperature results in flight for the first and second Data Collection satellites (SCD-1 and SCD-2) and for the first China Brazil Earth Resources Satellite (CBERS), recently launched, had shown the validity of the developed computational code.

Keywords: Direct Solar Radiation, Albedo, and Earth Radiation.

1. INTRODUCTION

The difference between space and terrestrial environments is the absence of atmosphere at the first one. On the ground the most common temperature control is made through air ventilation. Already, in satellites, this is not possible, due to the lack of the convective media so the control must be achieved by energy balance between the spacecraft emitted infrared radiation against the internal dissipated energy, which is dissipated by internal electric components added to the environmental absorbed energy. A body in space is submitted to different radiations where the sunlight is that one that most affects its temperature, but the albedo and the Earth IR emitted energy also must be considered. The direct solar radiation is the greatest environmental source of incident heating on most of the spacecrafts. Due to the Earth's elliptical orbit, the solar radiation that reaches the Earth, has a variation from about 3%, this means a range from 1326 W/m^2 at the summer solstice to a maximum of 1418 W/m^2 at the winter solstice (Smith & West, 1983). The Earth's albedo usually is expressed as percentage of the incident sunlight. In satellite thermal analysis, this percentage is taken as around 34% of the incident sunlight (Cunningham, 1963). The Earth itself, like a satellite, achieves the thermal equilibrium by balancing the Sun absorbed energy with the re-emitted one, as long-wavelength IR radiation. The intensity of Earth emitted infrared heat load can

vary considerably, depending on factors such as surface and air temperatures, atmospheric moisture and cloud coverage. As first approximation it is usual to take a value around 237 W/m² (Gilmore, 1994) for this re-emitted energy.

2. SOLAR RADIATION DETERMINATION

It is assumed that the direct solar radiation impinges upon the Earth and upon the satellite with parallel rays, due to the great distance between the Sun and Earth. With this assumption, the incident solar flux on a not shadowed surface by the Sun is simply given by the product of the solar constant times the surface projected area over a Sun vector perpendicular plane. Details of this can be found in Leite, (1986).

$$q_s = \bar{S} \cdot \bar{N} \quad (1)$$

where: \bar{N} = satellite surface normal vector and \bar{S} = Sun vector

Thus, to determine the incident direct solar radiation on a satellite it is necessary to obtain a relation between the Sun vector and the satellite positions in a same coordinate system. The Sun position is known through its right ascension (α_o) and declination (δ_o), defined at the geocentric inertial system, $X^i Y^i Z^i$, shown in Fig. 1. Thus, the Sun vector is given as:

$$\bar{S}^i = S(\cos\delta_o \cos\alpha_o \hat{i}^i + \cos\delta_o \sin\alpha_o \hat{j}^i + \sin\delta_o \hat{k}^i) \quad (2)$$

where: X^i = points in the direction of the point where the Equator crosses with the plane of the Earth's orbit about the Sun, from the south to the north (vernal point γ);

Y^i = is the Earth rotation axis in the north sense.

Z^i = completes the direct triad $X^i Y^i Z^i$

The satellite position in the orbit can be known defining its orbital elements in an orbital geocentric system $X^o Y^o Z^o$ as presented in Fig.2, as follows:

$$\begin{aligned} \bar{S}^o = & S \{ [-\sin(w+f)(\cos\Omega \cos\delta_o \cos\alpha_o + \sin\Omega \cos\delta_o \sin\alpha_o) + \\ & + \cos(w+f)(-\sin\Omega \cos\delta_o \cos\alpha_o \cos i + \cos\Omega \cos\delta_o \sin\alpha_o \cos i) + \sin i \sin\delta_o] \hat{i}^o + \\ & + [\sin\Omega \cos\delta_o \cos\alpha_o \sin i - \cos\Omega \cos\delta_o \sin\delta_o \sin i + \sin\delta_o \cos i] \hat{j}^o + \\ & + [\cos(w+f)(\cos\Omega \cos\delta_o \cos\alpha_o + \sin\Omega \cos\delta_o \sin\alpha_o) + \\ & + \sin(w+f)(-\sin\Omega \cos\delta_o \cos\alpha_o \cos i + \cos\Omega \cos\delta_o \sin\alpha_o \cos i) \sin\delta_o \sin i] \hat{k}^o \} \quad (3) \end{aligned}$$

where: i = orbit inclination, w = perigee argument, f = true anomaly, Ω = ascending node right ascension

Now considering the $X^s Y^s Z^s$ a reference system fixed at the satellite (see Fig. 3), where its origin is the mass center of the satellite, the Z^s axis coincides with its symmetry axis and is directed to the satellite's nadir. The X^s and Y^s axes are parallel to the satellite base, such as X^s is aligned with the lateral panel normal in the direction of satellite velocity and Y^s makes 90° with X^s forming a triad $X^s Y^s Z^s$. A relation between the satellite panels normals and the Sun vector, in this system, can be determined in relation to the geocentric orbital system as function of Euler angles ϕ_s , θ_s and ψ_s (see Fig. 3), which must be supplied along the orbit. Thus this relation is given by:

$$\begin{aligned}
\vec{S}^s = & S \left\{ \left[-\sin(w+f)(\cos \Omega \cos \delta_o \cos \alpha_o + \sin \Omega \cos \delta_o \sin \alpha_o) + \right. \right. \\
& + \cos(w+f)(-\sin \Omega \cos \delta_o \cos \alpha_o \cos i + \cos \Omega \cos \delta_o \sin \alpha_o \cos i) + \\
& + \sin i \sin \delta_o \left. \right] (\cos \phi_s \cos \psi_s - \sin \phi_s \sin \psi_s \cos \theta_s) + \\
& + \left[\sin \Omega \cos \delta_o \cos \alpha_o \sin i - \cos \Omega \cos \delta_o \sin \delta_o \sin i + \sin \delta_o \cos i \right] \times (-\sin \phi_s \cos \psi_s + \\
& + \sin \psi_s \cos \phi_s \cos \theta_s) + \left[\cos(w+f)(\cos \Omega \cos \delta_o \cos \alpha_o + \sin \Omega \cos \delta_o \sin \alpha_o) + \right. \\
& + \sin(w+f)(-\sin \Omega \cos \delta_o \cos \alpha_o \cos i + \cos \Omega \cos \delta_o \sin \alpha_o \cos i) + \left. \sin \delta_o \sin i \right] \times \\
& \left. (-\sin \theta_s \sin \psi_s) \right\} \hat{i}^s + \\
& + S \left\{ \left[-\sin(w+f)(\cos \Omega \cos \delta_o \cos \alpha_o + \sin \Omega \cos \delta_o \sin \alpha_o) + \right. \right. \\
& + \cos(w+f)(-\sin \Omega \cos \delta_o \cos \alpha_o \cos i + \cos \Omega \cos \delta_o \sin \alpha_o \cos i) + \\
& + \sin i \sin \delta_o \left. \right] (\cos \phi_s \sin \psi_s - \sin \phi_s \cos \theta_s \cos \psi_s) + \\
& + \left[\sin \Omega \cos \delta_o \cos \alpha_o \sin i - \cos \Omega \cos \delta_o \sin \delta_o \sin i + \sin \delta_o \cos i \right] \times (-\sin \phi_s \sin \psi_s + \\
& + \cos \phi_s \cos \theta_s \cos \psi_s) + \left[\cos(w+f)(\cos \Omega \cos \delta_o \cos \alpha_o + \sin \Omega \cos \delta_o \sin \alpha_o) + \right. \\
& + \sin(w+f)(-\sin \Omega \cos \delta_o \cos \alpha_o \cos i + \cos \Omega \cos \delta_o \sin \alpha_o \cos i) + \left. \sin \delta_o \sin i \right] \times \\
& \left. (-\sin \theta_s \cos \psi_s) \right\} j^s + S \left\{ \left[-\sin(w+f)(\cos \Omega \cos \delta_o \cos \alpha_o + \sin \Omega \cos \delta_o \sin \alpha_o) + \right. \right. \\
& + \cos(w+f)(-\sin \Omega \cos \delta_o \cos \alpha_o \cos i + \cos \Omega \cos \delta_o \sin \alpha_o \cos i) + \\
& + \sin i \sin \delta_o \left. \right] \cdot (\sin \phi_s \sin \theta_s) + \\
& + \left[\sin \Omega \cos \delta_o \cos \alpha_o \sin i - \cos \Omega \cos \delta_o \sin \alpha_o \sin i + \sin \delta_o \cos i \right] \times (\cos \phi_s \sin \theta_s) + \\
& + \left[\cos(w+f)(\cos \Omega \cos \delta_o \cos \alpha_o + \sin \Omega \cos \delta_o \sin \alpha_o) + \right. \\
& + \sin(w+f)(-\sin \Omega \cos \delta_o \cos \alpha_o \cos i + \cos \Omega \cos \delta_o \sin \alpha_o \cos i) + \left. \sin \delta_o \sin i \right] \times \\
& \left. \cos \theta_s \right\} \hat{k}^s
\end{aligned} \tag{4}$$

Therefore substituting Eq.(4) at Eq. (1) the angle of the incident direct solar radiation on the satellite external surfaces could be obtained.

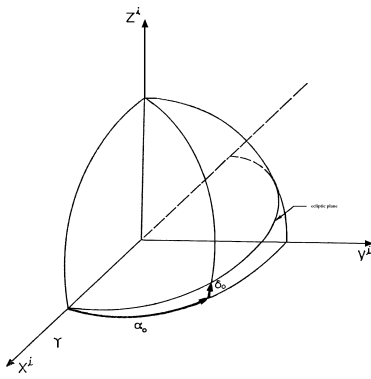


Figure 1 Inertial Geocentric System

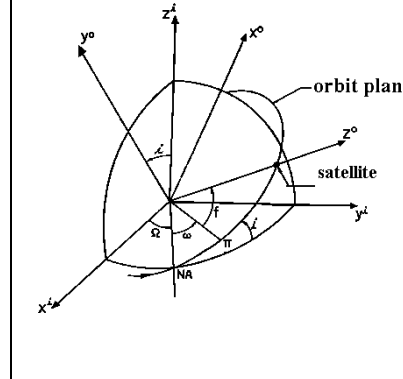


Figure 2 Orbital Geocentric System

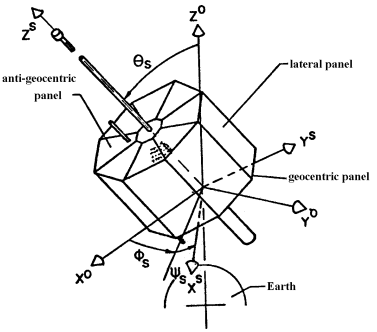


Figure 3 Satellite System

2.1 Satellite passage through Earth shadow

Assuming a low and circular orbit, the rate between the time that the satellite is in sunlight and the orbit period, is denominated insolation factor (ψ). This rate varies with the angle (ξ) between the Sun vector and the orbit plane (Fig. 4), and with the satellite distance

from the Earth center. A cylinder could approximate the Earth shadow, and its projection over the orbital plane has a semi-elliptic form, its semi-minor axis is equal to the Earth ray (R_T) and semi-major axis $R_{so} = R_T / \sin \xi$ (Fig. 5). The equation of this ellipse is given by:

$$\frac{x^2}{(R_T / \sin \xi)^2} + \frac{y^2}{(R_T)^2} = 1 \quad (5)$$

and the satellite orbit equation could be parameterized in function of ϕ_o (the semi-angle spent by the satellite inside the shadow): $x = R \cos \phi_o$ and $y = R \sin \phi_o$, where the ϕ_o angle could be determined as function of ξ :

$$\phi_o = \tan^{-1} \left(\frac{(R_T)^2 - R^2 \sin^2(\xi)}{R^2 - (R_T)^2} \right)^{1/2} \quad (6)$$

The insolation factor (ψ) could be determined, since it is given by $\psi = (\pi - \phi_o) / \pi$. As shown by Leite, 1986, the time that the satellite keeps illuminated grows with the ξ angle and with the satellite altitude.

The satellite thermal design is done for the critical conditions of this design. These conditions can occur during the satellite lifetime and to lead satellite equipments reach their maximum and minimum temperatures. Thus, the angle ξ is very useful for visualizing the orbital thermal environment, particularly for the critical design conditions definition. This angle is determined mathematically (Leite, 1986) in function of the orbital parameters and of the Sun inertial coordinates as follows:

$$\sin \xi = \sin i \cos \delta_o \sin(\Omega - \alpha_o) + \cos i \sin \delta_o \quad (7)$$

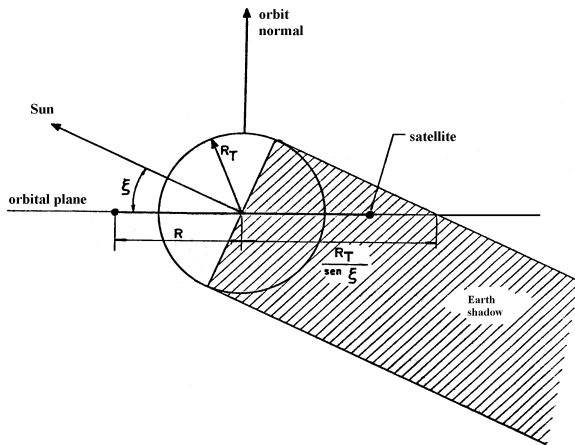


Figure 4: Earth shadow cylinder

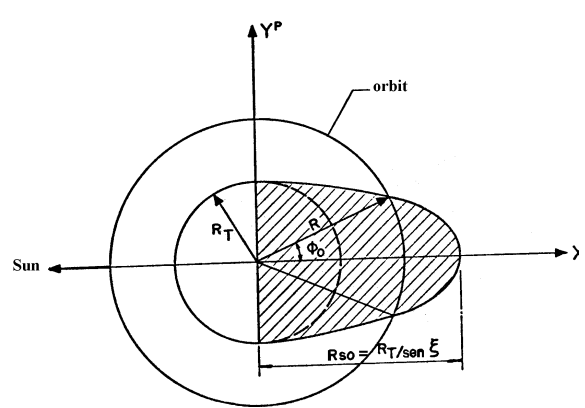


Figure 5: Earth shadow on the orbit plane

3. ALBEDO DETERMINATION

The albedo of the Earth is the fraction of the total incident solar radiation that is reflected into space as a result of scattering in the atmosphere and reflection from clouds and surface. The albedo coefficient is a function of the Earth topography and meteorological conditions, and can vary from 0.10 to 0.80. Redor (1973) and Gilmore (1994) proposed an average value

of 30% for Earth albedo using data acquired by spacecrafts. In the albedo calculations, it generally is assumed that the albedo coefficient is a constant for the Earth and that the Earth surface emits diffusely, obeying to Lambert's law.

The albedo is obtained numerically and the integration limits are established by the condition that only those area elements of the Earth, which are simultaneously visible from the satellite and illuminated by the Sun, are taken into account. The way in which is made the flux calculation is shown in Fig. 6. The Z^a axis points towards the satellite and the Sun is in the Y^aZ^a plane. The expression for the incident albedo upon a flat unitary area plate, which is spinning about an axis, coincident with the spin axis of the satellite, will be:

$$q_a = \int_{A_T} \frac{\alpha S \cos v_s}{\pi} \cdot \cos \delta_s \cdot \frac{\cos \eta}{|\bar{\rho}^a|^2} \cdot dA_T \quad (8)$$

where: α = mean albedo, S = mean solar constant, dA_T = the infinitesimal terrestrial surface area element over which the function is integrated, v_s = the angle between the solar vector and dA_T , δ_s is the angle between the dA_T and $\bar{\rho}^a$, η = the angle between the normal to the plate and $\bar{\rho}^a$.

From the geometric problem the following relations could be obtained:

$$\cos v_s = \sin \theta \cos \phi \sin \theta_s + \cos \theta \cos \theta_s \quad (9)$$

$$\cos \delta_s = \frac{r \cos \theta - 1}{(r^2 - 2r \cos \theta + 1)^{1/2}} \quad \text{where:} \quad r = (R_T + h)/R_T \quad (10)$$

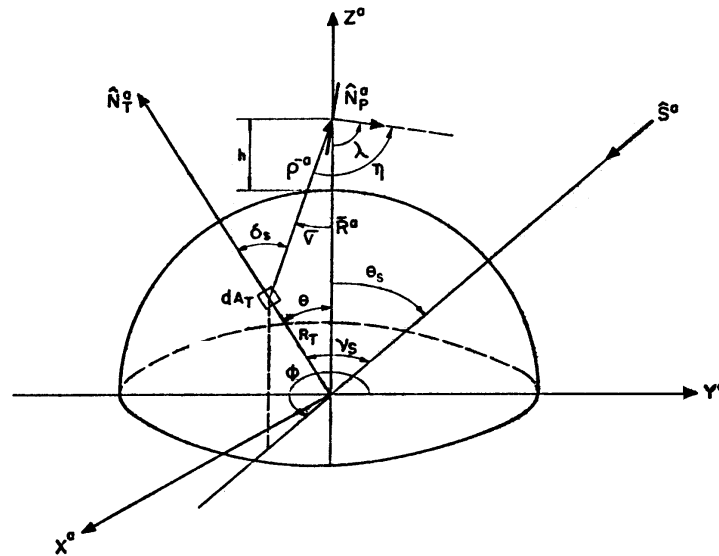


Figure 6 Problem geometry

To find an expression for $\cos \eta$, it is necessary to define a new angle ζ (see Fig. 7) that makes the plate positioning in relation to Y^aZ^a , in which the Sun vector (\bar{S}^a) is met. The azimuth angle ζ defines the plate rotation around the satellite spin axis ($\bar{\omega}^a$), which coincides with vector \bar{R}^a . Thus, the expression for $\cos \eta$ could be given as:

$$\cos \eta = \frac{\sin \lambda \sin \theta (\cos \zeta \cos \phi + \sin \zeta \sin \phi) + (r - \cos \theta) \cos \lambda}{(r^2 - 2r \cos \theta + 1)^{1/2}} \quad (11)$$

From Fig. 8 the following terms could be obtained:

$$dA_T = (R_T)^2 \sin \theta d\theta d\phi \quad \text{and} \quad |\vec{p}^a| = R_T (r^2 - 2r \cos \theta + 1)^{1/2} \quad (12)$$

Replacing Equations (9) - (12) in Eq. (8) the expression for the incident albedo on an unitary area plate is given by:

$$q_a = \frac{\alpha S}{\pi} \int_{\theta} \int_{\phi} \frac{1}{(r^2 - 2r \cos \theta + 1)^2} \cdot \{(r \cos \theta - 1) \cdot (\sin \theta \cos \phi \sin \theta_s + \cos \theta \cos \theta_s) \cdot [(r - \cos \theta) \cos \lambda + \sin \theta \sin \lambda (\cos \zeta \cos \phi + \sin \zeta \sin \phi)] \sin \theta\} d\theta d\phi \quad (13)$$

Equation (13) must be integrated over total Earth surface, visible from the satellite and illuminated by the Sun simultaneously. A procedure to determine the integration limits in θ and ϕ for Eq. (13) is presented in Leite (1986).

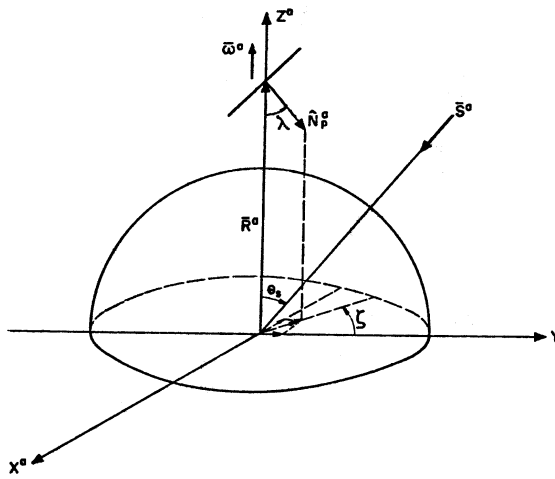


Figure 7 Plate position in relation to Sun vector

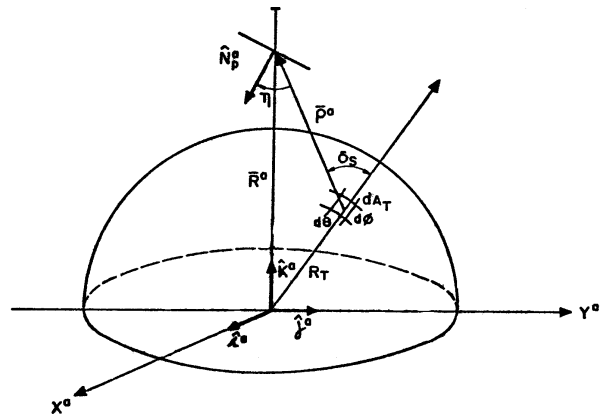


Figure 8 Area element on the Earth

4. EARTH RADIATION DETERMINATION

The same assumptions as those made for albedo (uniform intensity and Lambertian emission) are used in the calculations of Earth radiation. The intensity of the emitted infrared energy can also vary considerably, depending on factors such as surface and air temperatures, atmospheric moisture and cloud coverage. Gilmore (1994) proposed as first approximation to use a value around 237 W/m^2 for energy emitted by the Earth surface.

The expression for the incident Earth radiation on a plate of unitary area, with arbitrary orientation in relation to the local vertical, considering the same reference system shown in Fig. 6 and the same geometry shown in Fig. 7, is given by:

$$q_e = \int_{A_T} \frac{\sigma T_e^4}{\pi} \cos \delta_s \cdot \frac{\cos \eta}{|\vec{p}^a|^2} \cdot dA_T \quad (14)$$

where σ = Stephan-Boltzmann constant, T_e = mean temperature of the Earth ($\sigma T_e^4 / \pi$) $\cdot \cos \delta_s$ is the radiant energy per time unity, unitary area and solid angle in the plate direction, and $\cos \eta / |\vec{p}^a|^2$ is the solid angle understood by the plate in dA_T .

Replacing Equations (10), (11) and (12) in Eq. (14), the expression for incident Earth radiation on the plate will be:

$$q_e = \frac{\sigma T_e^4}{\pi} \int_{\theta} \int_{\phi} (r \cos \theta - 1) [\sin \lambda \sin \theta (\cos \zeta \cos \phi + \sin \zeta \sin \phi) + (r - \cos \theta) \cos \lambda] \frac{\sin \theta}{(r^2 - 2R \cos \theta + 1)^2} d\theta d\phi \quad (15)$$

The integration limits for the variables θ and ϕ were obtained considering the plate orientation in relationship to the Earth surface visible region and are detailed in Leite (1986). In this case, the integration limits for the variable ϕ do not depend anymore on the angle (θ_s) which makes the Sun vector positioning the in relation to the local vertical.

5. COMPUTATIONAL CODE (CATER)

A computational code (CATER) was developed and implemented for the determination of the incident direct solar radiation, albedo and Earth radiation on satellites in low Earth orbits. The computational code was developed in Fortran, using the algorithm "SQUANK" (Simpson quadrature used adaptively – noise killed from Lyness, 1970) for the numeric integration of the obtained expressions for the albedo and Earth radiation. The program was validated using comparisons between the results obtained by the code and the results available at literature as presented by Leite, 1986.

6. RESULTS COMPARISON

At first the computational program was developed to determine the incident external thermal loads on first satellite of the Brazilian Complete Space Mission (MECB), i e, the First Data Collection Satellite (SCD-1). Afterwards, it has been used for the incident external loads on all the other satellites of the Brazilian Space Program. The results obtained by CATER for the incident external thermal loads on the satellites SCD-1, SCD-2 are presented by Leite (1986) and Cardoso (1990), respectively. These results could not be validated by tests, since that a solar simulator that would simulate the Sun distribution, collimation and intensity is not available at INPE.. However, with the launching of SCD-1 in 1993 and of SCD-2 in 1998 the temperature telemetries of these satellites in flight could be obtained. Consequently, these temperatures were measured in flight and compared with the predicted temperatures to these satellites by the INPE's satellite thermal control group. It was verified a difference less than 5°C between measured temperatures and the calculated temperatures, these values are exactly within the considered thermal design margin. Thus, it was possible to conclude that these external load results obtained by CATER are good and reliable. For CBERS satellite, developed in partnership with Republic Popular of China, launched at October 1999, the incident external thermal loads on its structural and solar panels were calculated by brazilian thermal control group using CATER and also by the chinese engineers from CAST (Chinese Academy of Space Technology) with their own software. Figures 9 and 10 present a comparison between the results obtained by both sides. The shown results were obtained for critical conditions of the thermal design, where the maximum (hot case) and minimum (cold case) temperatures were found for CBERS. In the same way, the obtained temperature telemetries in flight for CBERS, since its launching also confirm that the obtained results for the incident external thermal loads on it are correct.

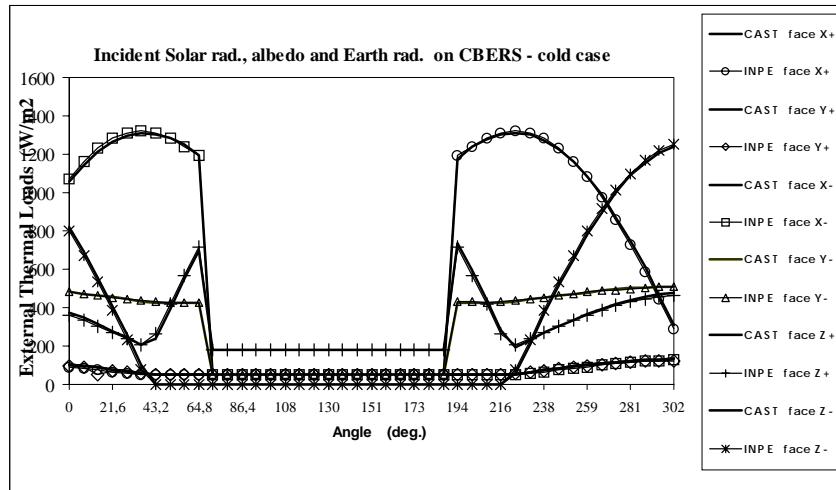


Figure 9 Environment incident thermal loads on CBERS for the cold case

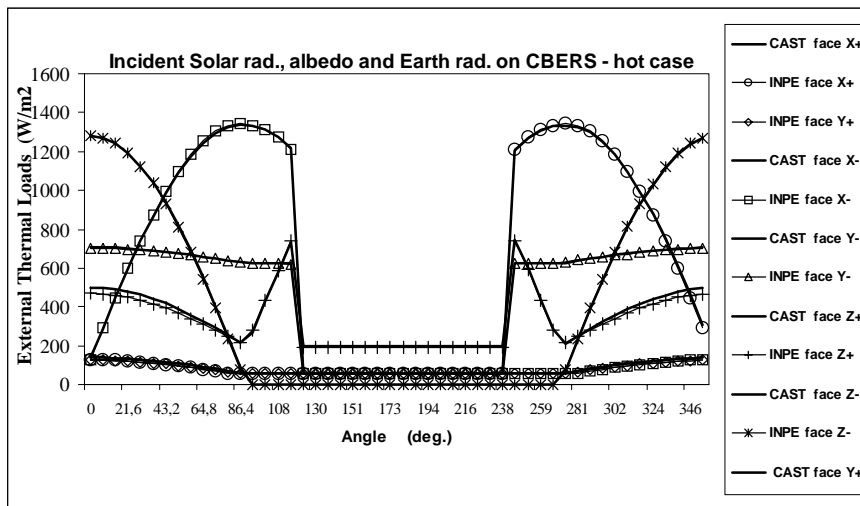


Figure 10 Environment incident thermal loads on CBERS for the hot case

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