EXTERNAL HEAT LOAD PREDICTIONS IN STEADY STATE CONDITION FOR THE ITASAT SATELLITE

Douglas Felipe da Silva[1], dfsilva@ita.br
Ezio Castejon Garcia[1], ezio@mec.ita.br
[1]Instituto Tecnológico de Aeronáutica, Divisão de Engenharia Mecânica-Aeronáutica, Praça Marechal Eduardo Gomes, 50, Vila das Acácias, CEP 12.228-900, São José dos Campos-SP.

Abstract. *This work presents the external heat load predictions, in steady state condition, which the ITASAT (an experimental satellite developed by Technological Institute of Aeronautics - ITA) will be submitted. This analysis is done for flight critical cases. ITASAT will be the first Brazilian duty satellite developed by universities, and its main function will be data relay. This program is being directed by ITA with collaboration of others Brazilian universities. National Institute of Space Researches (INPE) technical supports and the Brazilian Space Agency (AEB) sponsors the program. The commercial program SINDA/FLUINT was used as computational platform. This one has the feature of calculating external heat loads (solar radiation, terrestrial radiation and albedo) on a given artificial satellite in orbit, and also calculate the internal heat loads deriving from equipment that compose the satellite. Parameters such as orbit type and attitude of the satellite influence directly in the intensity of these loads. In the future works will be possible to calculate the temperature distribution in the satellite associating these loads with the internal heat dissipations of the equipment. This study is part of the thermal control project that will guarantee that the high and low acceptable temperature limits for all equipment. The presented results are physically coherent for Low Earth Orbit satellites.*

Keywords*: Satellite, ITASAT, External Heat Loads, Thermal Control.*

1. INTRODUCTION

Due to the absence of atmospheric convection in space, overall thermal control of a satellite on orbit is usually achieved by balancing the energy emitted by the spacecraft as infrared radiation (IR) against the energy dissipated by internal electrical components plus the energy absorbed from the environment. Spacecraft thermal control is a process of energy management in which environmental heating plays a major role. The main forms of environmental heating on orbit are sunlight, both direct and reflected off of the Earth, and IR energy emitted from the Earth itself. During launch or in exceptionally low orbits there is also a free molecular heating effect due the friction with the rarefied upper atmosphere (Gilmore, 1994).

The numerical thermal model is the working tool in the development of a satellite thermal control system. It is used to predict temperatures on a large scale, with most structures and others components interacting with one another and with surrounding environment. Generating the thermal model begins early in a satellite project, with additions and upgrades continuing as notions on design and performance become firmer. Final confirmation follows the thermal balance test, conducted in a vacuum chamber, when predictions from the model are correlated with test results (Karam, 1998).

ITASAT program is a development multidisciplinary project that involves ITA, AEB, INPE and others Brazilian universities. This program has been an initiative of the ITA under-graduate students. In this stage, the staff is mainly composed with under-graduates and graduate students, but the project is normally reviewed in order to get the whole school involvement.

ITASAT program has the purpose to design, develop, manufacture, integrate, test, launch and, operate a technological microsatellite. On-orbit, the program will validate an integrated system composed by an Attitude Control and Data Handling (ACDH), a Global Positioning System (GPS) and two others payloads: a Data Collecting Subsystem (DCS) and other scientific experiment system (to be defined).

This paper presents results of a numerical simulation of average heat load (steady-state condition) prediction for the ITASAT. The flight critical cases, end of life (EOL) and begin of life (BOL), were simulated to evaluate the incident and absorbed heat fluxes. Data reported by “Leite, (1986)” and “Abouel-Fotouh *et al*. (2006)” are used to validate the model.

1.1. ITASAT satellite

ITASAT satellite does not have yet a final defined configuration (May, 2009). A preliminary definition is that the satellite will have two functions: one operational and other experimental. The operational function is to collect environmental data (manly weather data). For this purpose, ITASAT will have a Data Collection Transponder as main payload. The intention is to replace the Collect Data Satellites #1 and #2 (SCD1 and SCD2), in which were launched in 1993 and 1998, respectively. The ITASAT satellite will utilize low Earth orbit: circular, 750 km height, 25 degrees of inclination. For this kind of orbit, the satellite will remain at Earth tropical zone. Orbits whose maximum altitude are less than approximately 1800 kilometers are generally considered low Earth orbits (LEO), and have short periods, around of 100 minutes. The inclination and altitude of the ITASAT orbit will be the same of the SCD2 satellite. This inclination allows the satellite to cover Brazil's territory, region where the INPE's data collect platforms are placed. Thus, when it passes over Brazil, the data sent by the satellite's transponder will be received by the ground antennas.

ITASAT will be a spin-stabilized satellite, thus, it will spin around its own "Z" axis, with approximately 40 rotations per minute and will have a pointing of 0.5° relative to the Earth's geomagnetic field. The satellite's pictures are shown in "Fig. 1".

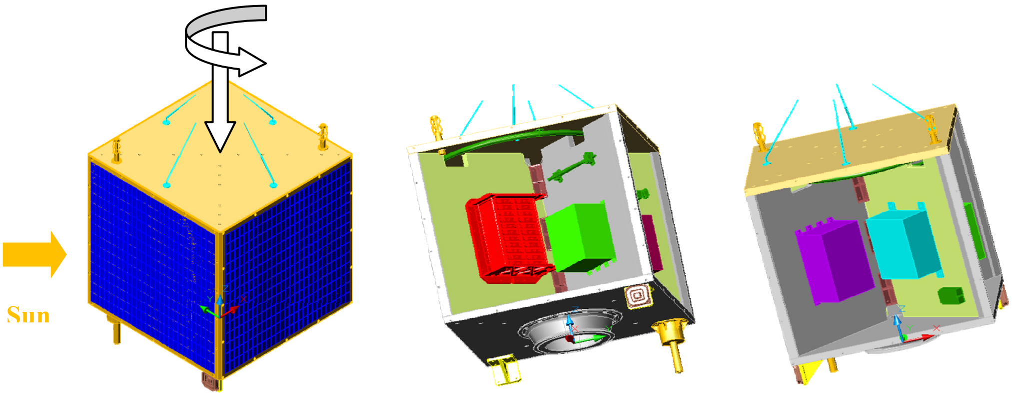

Figure 1. ITASAT's structure, with anticlockwise rotation around "Z" axis.

The satellite's dimension can be approximated to a parallelepiped with 0.70 m in the X direction, 0.70 m in the Y direction and 0.65 m in the Z direction. The satellite, including the antennas and others equipment, must be placed into a cylindrical shell with approximately 1 m of diameter, to ensure compatibility with the launch vehicle, and also, its mass, should not exceed 80 kg.

The solar arrays will be placed parallel to spin's axis, to ensure the necessary illumination to generate the required power, and inside the box, the internal panels are placed in "X" shape, crossing from each corner to the opposite side. ITASAT will be composed by the structure subsystem, electrical power/distribution subsystem (EPS or EPDS), telemetry, tracking and command subsystem (TT&C), attitude/velocity control subsystem (ACS or AVCS) and thermal control subsystem (TCS).

The thermal control subsystem (TCS) is presented in all satellite. Its purpose is to maintain all equipment of the spacecraft within their respective temperature limits. There are several different sources of thermal energy acting on a spacecraft: solar radiation, albedo, Earth emitted infrared, and heat generated by on-board equipment. Therefore, the thermal control subsystem is different for every spacecraft. In general, there are two types of TCS: passive and active. A passive system relies on conductive and radiative heat paths and has no moving parts or electrical power input. An active system is used in addition to the passive system when passive system is not adequate. Active systems rely on pumps, thermostats, and heaters, use moving parts, and require electrical power (Fischer, 1995).

The thermal features of the ITASAT, as low power, low Earth orbit and spin-stabilized, collaborate to obtain the temperatures inside of the limits employing only passive thermal control. Low Earth orbit results on low orbital period and short eclipse time, resulting on decreasing of temperature instability between the shining and the eclipse periods. In thermal point of view, the spin-stabilized is a positive factor, because it results in a temperature homogenization. The TCS concept for the ITASAT satellite should be similar to the SCD-1 satellite, where only passive thermal control material has been employed.

2. EXTERNAL HEAT LOADS

The sources of thermal radiation establish the external heat load intensity that the satellite will be submitted. The main incident radiation sources at a satellite are: direct solar radiation, albedo (solar radiation reflected by Earth) and infrared radiation emitted by Earth. The heat quantity received depends on the radiation intensity and, for albedo and Earth radiation, depends on the shape factor between the considered surface and Earth.

The overall thermal control of a satellite on orbit is usually achieved by balancing the energy emitted by the spacecraft as infrared radiation against the energy dissipated by internal electrical equipment plus energy absorbed from the environment. The sources of external heat loads are described bellow. In this paper, another heat sources, as the free molecular heating effect due to friction with rarefied upper atmosphere, are not considered.

2.1. Direct Solar

Sunlight is the greatest source of environmental heating incident on most spacecraft. The emitted radiation from the sun is constant within a fraction of 1 percent at all times. However, due to the Earth's elliptical orbit, the intensity of sunlight reaching the Earth varies approximately ±3.5% depending on the Earth's distance from the sun. At summer solstice (northern hemisphere) the intensity is at a minimum (1310 W/m²) and at a maximum (1400 W/m²) at winter solstice. The solar intensity also varies as a function of wavelength (Gilmore, 1994). The spectral distribution is about 7% UV in the 0.31-0.40 µm range, 46% visible (0.40-0.69 µm), and 47% IR above 0.70 µm. Solar IR has shorter wavelengths than the IR emitted at normal satellite temperatures and one can take advantage of this difference and condition a surface to have simultaneously a high reflectivity in the solar spectrum and high emissivity in long-wave IR. The property connected with this idea is solar absorptivity α^i, which is the fraction of unhindered solar energy that is absorbed by the surface, and is given by "Eq. (1)" (Karam, 1998).

$$S^a = \alpha^i S \cos\theta \tag{1}$$

Where:

S is the solar vector's magnitude;
S^a is the solar energy absorbed;
θ is the angle between the solar vector and the surface's normal;
α^i is the absorptivity in the solar spectrum.

2.2. Albedo

Albedo is the heating from sunlight reflected off by Earth. It is usually considered to be in same spectrum as solar radiation and often quoted as a fraction of the solar constant. The albedo value is given by "Eq. (2)".

$$A = f\,S \tag{2}$$

Where:

A is the albedo;
f is the albedo factor;
S is the solar vector's magnitude.

Albedo appears more significant at the Earth's polar ice caps and can be estimated in those regions with some accuracy as a function of the sun's elevation and the satellite's orbital parameters. However, predictions for overland and above oceans become distorted by the highly variable effects of cloud formations and water distribution in the atmosphere. "Table 1" presents the albedo factor as a function of orbit inclination (Karam, 1998).

Table 1. Albedo factor as function of orbit inclination.

Orbit inclination	f (NASA TM-82478)		
	minimum	average	maximum
±90 °	0.38	0.42	0.46
±80 °	0.34	0.38	0.42
±70 °	0.30	0.34	0.38
±60 °	0.26	0.30	0.34
±50 °	0.22	0.28	0.32
±40 °	0.19	0.25	0.29
±30 °	0.20	0.24	0.28
±20 °	0.20	0.24	0.28
±10 °	0.20	0.24	0.28

2.3. Earth emission

The Earth not only reflects sunlight, it also emits long-wave infrared (IR) radiation. The Earth, like a satellite, achieves thermal equilibrium by balancing the energy received (absorbed) from the sun with the energy re-emitted as long-wavelength IR radiation. This balance is maintained fairly well on a global annual average basis. The intensity of

IR energy emitted at any given time from a particular point on the Earth, however, can vary considerably depending on factors such as surface and air temperatures, atmospheric moisture content, and cloud coverage. As a first approximation one can use a value around 236.5 W/m² emitted at the Earth's surface.

The IR energy emitted by the Earth, which is around 255 K, is of approximately the same wavelength as that emitted by satellites, that is to say, it is of much longer wavelength than the IR energy emitted by the sun at 5800 K. Unlike short-wavelength solar IR, the Earth IR loads cannot be reflected away with special thermal control coatings since the same coating, would prevent the radiation of waste heat away from the spacecraft. Because of this, Earth-emitted IR energy can present a particularly heavy backload on spacecraft radiators in low-altitude orbits, which must emit energy at the same wavelength (Gilmore, 1994).

3. SIMULATION'S CHARACTERISTICS

Environment fluxes must be know to calculate the normal incident fluxes that contribute to the heating of an orbiting satellite. Also needed for this calculation are orbit dates, inclination, eccentricity, elevation, and satellite surface orientations with respect to the sun and Earth. Dates relate Earth's distance from the sun, and altitudes define the reduction in the intensities of Earth flux and albedo that, when considered diffuse, are inverse functions of the distance squared. Orbit inclination and eccentricity define the orbital period and the times the satellite spends in sunlight and Earth shadow. Surface orientations are used to find the normal component of incident flux (Karam, 1998).

One parameter that acts directly on the incident fluxes in Low Earth Orbit is know as beta angle, β, defined as the angle the solar vector makes with the orbit plane. Because of Earth's oblateness and the sun's right ascension from vernal equinox and declination from the equatorial plane, the beta angle varies continuously over a year, passing through zero and reaching a maximum equal to the absolute value of the sum of orbit inclination and the ±23.5 deg greatest solar declination. Hence, incident fluxes calculated with the beta angle as a variable will provide the whole range of orbital heating (Karam, 1998).

As viewed from the sun, a β=0 deg orbit would appear edgewise. A satellite in such orbit would pass over the sub-solar point on the Earth where albedo loads are the highest, but it would also have the longest eclipse time due to shadowing by the full diameter of the Earth. As the β angle increases, the satellite pass over areas of the Earth further from sub-solar point, thereby reducing albedo loads; however, the satellite will also be in the sun for a larger percentage of each orbit due to decreasing eclipse times. At some point, which varies depending on the altitude of the orbit, eclipse time drops zero. At a beta angle of 90 deg a circular orbit appears as a circle as seen from the sun, there are no eclipses no matter what the altitude, and albedo loads are near zero (Gilmore, 1994). The variations of the beta angle are shown in "Fig. 2".

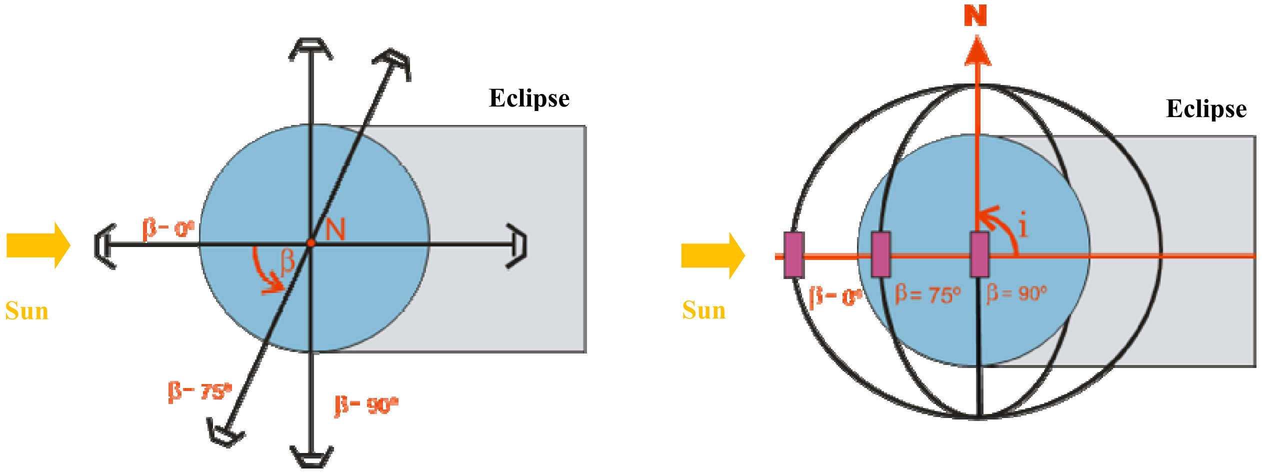

Figure 2. Different values of beta angle when seen from North Pole and Equator (Schelckle, 2008).

As seen before, the beta angle acts directly on the time that the satellite will be exposed to the external heat loads. "Figure 3" shows how eclipse times vary with beta angle for circular orbits of different altitudes.

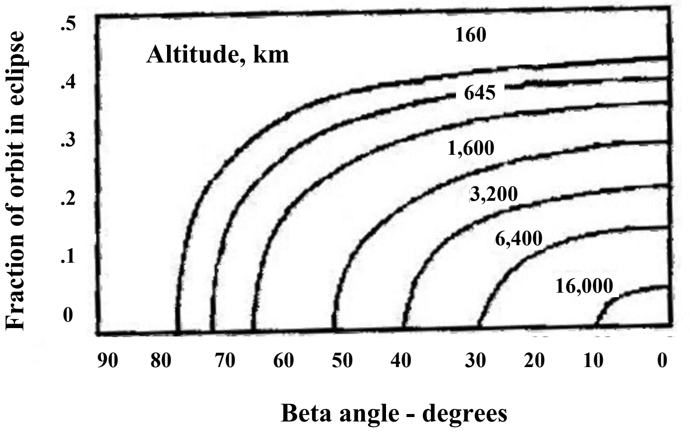

Figure 3. Eclipse durations (Gilmore, 1994).

3.1. Hot Case and Cold Case

To contend with errors, tolerances, and spacecraft uncertainties, thermal engineers almost universally adopt hot case (EOL) and cold case (BOL) analyses to define upper and lower bounds on predicted temperatures. The power profile for a hot case analysis may correspond to an operation in which the components' activity results in high dissipation, while the orbit is such that the radiators are exposed to considerable combined solar, albedo and Earth heating. Biased margins and tolerances are then imposed on power, environment heating fluxes, and thermal properties in a direction that makes the analysis produce the maximum possible temperature. Similarly, the input data from the cold case are selected to result in a calculated lowest temperature (Karam, 1998). The orbital parameters considered on simulation are shown in "Tab. 2".

Table 2. Orbital parameters.

Parameter	Cold Case	Hot Case
Beta angle	1.6 °	48.4 °
Solar radiation	1300 W/m²	1400 W/m²
Albedo	20%	30%
Earth radiation	198 W/m²	274 W/m²
Eclipse time	2111.7 s	1588.3 s

The external faces of the satellite's panels are coated by the following materials: i) Dupont's Kapton® film on the superior panel; ii) solar cells on the lateral panels; iii) Sheldahl's G 407912 film on the inferior panel; iv) Black paint on launcher interface flange. The employed material's optical thermal properties, like solar absorptivity, infrared emissivity and the relation between both, are shown in the "Tab. 3":

Table 3. Material's optical thermal properties.

Coating	BOL			EOL		
	α_{solar}	ε_{ir}	$\alpha_{solar}/\varepsilon_{ir}$	α_{solar}	ε_{ir}	$\alpha_{solar}/\varepsilon_{ir}$
Aluminized Kapton®Sheet	0.34	0.55	0.618	0.41	0.55	0.745
Black paint	0.9	0.9	1	0.9	0.9	1
Sheldahl's G407912 film	0.3	0.03	10	0.36	0.03	12
Solar cells	0.85	0.85	1	0.85	0.85	1

3.2. Calculation methods

The commercial software employed (in the ITASAT thermal project) is called SINDA. This is a software pack (Thermal Desktop, Radcad, Sinaps Plus and SINDA/FLUINT*)* commercialized by C&R Technologies (www.crtech.com) that has a good interface with AutoCAD, and makes easy the heat load's calculation, resulting on temperature's distribution, making the orbit sketch and allowing the satellite's geometry assembly utilizing AutoCAD's environment.

Thermal Desktop™ is a program that allows the user to quickly build, analyze, and postprocess sophisticated thermal models. Thermal Desktop takes advantage of abstract network, finite difference and finite element modeling methods. RadCAD is the radiation analyzer module for Thermal Desktop. An ultra-fast, oct-tree accelerated Monte-Carlo raytracing algorithm is used by RadCAD to compute radiation exchange factors and view factors. The output of Thermal Desktop and RadCAD is automatically combined for input into SINDA/FLUINT, thermal analyzer. SINDA/FLUINT does not use nor enforce the use of geometry. Rather, it is an equation solver based not on a geometric description of a system but on an abstract mathematical (circuit or network) description. Radiation exchange, however, normally requires geometry to produce infrared radiation conductances ("RADKs") and absorbed solar fluxes. Also, manual generation of nodal capacitances and linear conductances using finite difference approximations is both tiring and error-prone, and nullifies integration with the design database. SINDA/FLUINT can solve finite element equations if they have been transformed into a network-style formulation.

4. SIMULATION'S RESULTS

Much of the preceding relates to finding temperatures under steady-state conditions, defined either by orbit average values of dissipation and absorbed flux or as extended durations in a fixed orientation with respect to the heating source. It has been noted that averaging is often used in evaluating the thermal performance of platforms laden with massive electronics. The approach is suitable for predicting mission temperature limits and is very convenient in that solution routines do not involve stability or complicated convergence criteria.

Monitored thermistor data from orbiting satellites give credence to orbital averaging for component platforms where variations in the electronics dissipation are not too significant during the course of an orbit. Thermal designs of main canisters are generally directed toward reduced influences by environment fluxes, and in most cases of normal operation the mounting platform vacillates within ± 2 °C of the orbital average profile. These variations, and others that might occur momentarily during special events, can be predicted from greatly reduced models confined to the particular component and its immediate neighborhood, with the truncated surroundings usually replaced by sinks at constant orbital average temperature (Karam, 1998).

Due to the small temperature variation in some equipment, the average orbital heating rates can supply significant information with a reduced cost of analysis and tests. "Figure 4"presents the incident heat flux percentage for cold case.

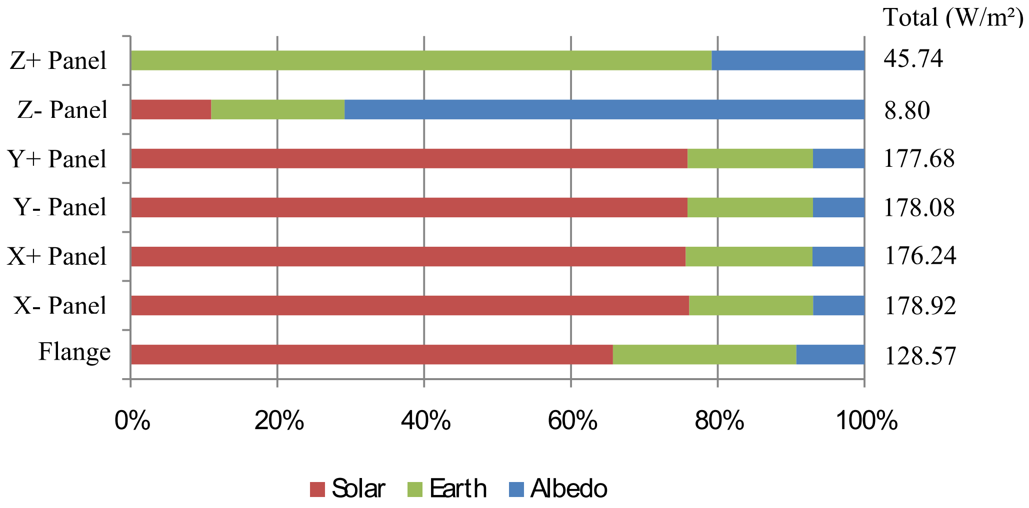

Figure 4. Percentage of incident heat flux for cold case.

By analyzing "Fig. 4", it should be noted that the solar radiation is the greatest source of heating in the satellite. Otherwise in the Z+ and Z- panels, the solar radiation is almost zero due the relative position between the panels and the solar vector. The Earth IR radiation acts in all elements, with more intensity in Z+ panel. The same behavior occurs to the hot case analysis, and the results are presented in "Fig. 5".

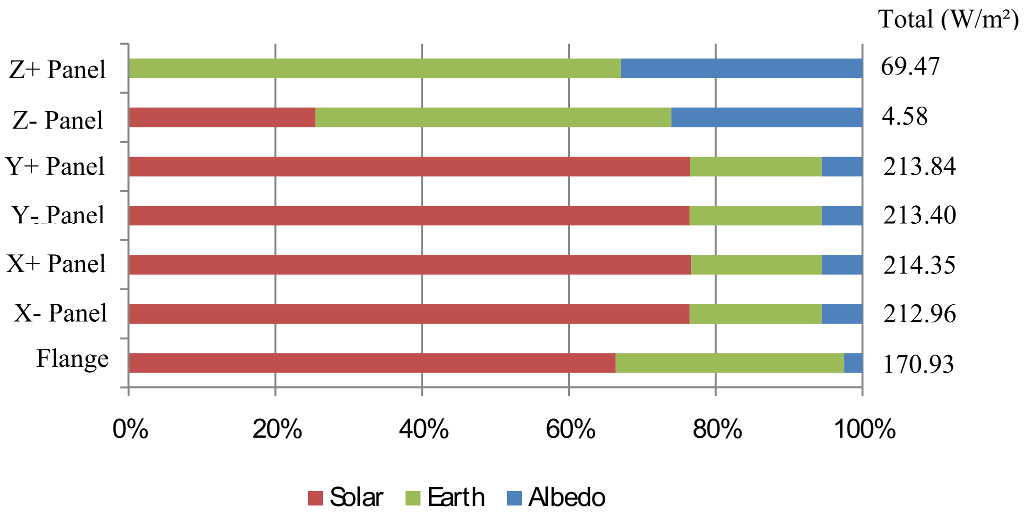

Figure 5. Percentage of incident heat flux for hot case.

The values of the absorbed heat flux will vary accordingly to surface's thermal optical properties. As explained before, to the solar wavelength the value of the incident heat flux should be multiplied by the solar absoptivity to obtain the absorbed flux. To the IR wavelength, the value of the incident heat flux will be multiplied by the IR emissivity to obtain the absorbed flux. "Figure 6" presents the time average absorbed heat flux for cold case analysis.

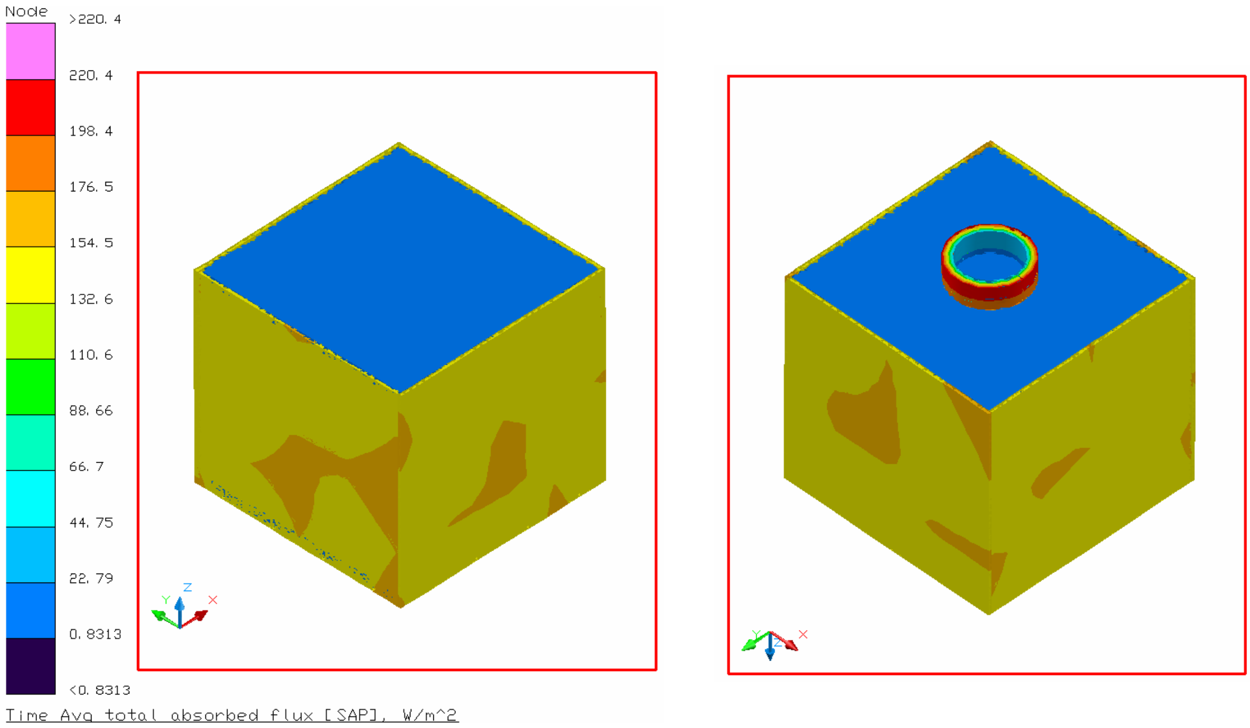

Figure 6. Time average total absorbed heat flux for cold case.

As presented in "Fig. 6" the absorbed heat flux on inferior and superior panels is less intense than the laterals panels. Flange absorbs radiation during all time that the satellite remains in orbit, and the highest value of the absorbed heat flux occurs on it. The profile of the absorbed heat flux presents the same behavior to the hot case analysis, and the results are shown in "Fig. 7".

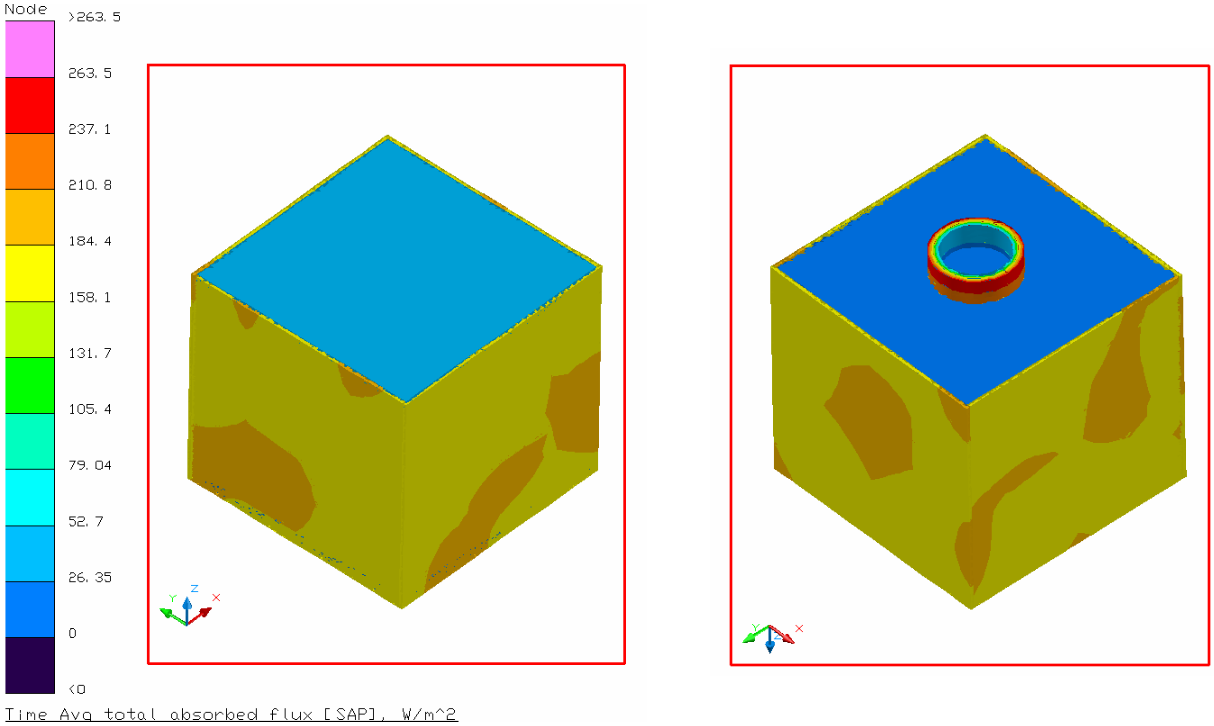

Figure 7. Time average total absorbed heat flux for hot case.

As expected, the difference between the results presented in "Fig. 6" and "Fig. 7" is just in the intensity of the total absorbed heat flux, as indicated in the figures' labels.

5. CONCLUSIONS

The values obtained in the average absorbed heat flux are normally expected for a spin-stabilized satellite, with low Earth orbit. As expected for a spin-stabilized satellite, the absorbed heat flux has almost the same intensity for all laterals panels, and the major source of heat is the solar radiation. The results obtained in this numerical simulation, provide a good preliminary reference for the ITASAT thermal control design. With this preliminary information, a coating selection can be fulfilled and the temperature distribution for steady state condition can be obtained. This simulation has the purpose of provide initial information for initial thermal design. In resume, it can said, that all obtained results of this paper showed themselves, physical coherent and suitable for the low Earth orbit satellites.

6. REFERENCES

Abouel-Fotouh A.M., Shabaka I., Elsharkawy A. and Elfar, 2006, "Material Selection for Satellite Passive Thermal Control", Journal of Applied Sciences Research, INSInet Publication, pp 1106-1111.

Fischer, M., Editor, 2007, "Thermal Control". 10 Sep. 2007, <www.tsgc.utexas.edu/archive/subsystems/thermal.pdf>.

Gilmore, D. G., Editor, 1994, "Satellite Thermal Control Handbook", The Aerospace Corporation Press, El Segundo, California.

Karam, R. D., 1998, "Satellite Thermal Control for System Engineers", Progress in Astronautics and Aeronautics, Vol. 181, AIAA, Cambridge, 274p.

Leite, R. M. G., 1986, "Modelagem das Cargas Térmicas Incidentes nos Painéis do Primeiro Satélite Brasileiro", Dissertação de Mestrado, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brasil.

Schelckle, M., 2007, "Small Satellite Design**".** 7 Mar. 2008, < www.irs.uni-stuttgart.de/skript/KSE/KSE-WS051104_www.pdf>.

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