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ANALYSIS OF EXTERNAL HEAT LOADS FOR THE ITASAT SATELLITE IN TWO ATTITUDE CONTROL CONFIGURATIONS: SPIN AND 3-AXIS STABILIZATIONS

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Abstract: *This work presents the average (steady state condition) and transitory external heat load predictions that ITASAT, an experimental satellite developed by Technological Institute of Aeronautics, will be submitted. This analysis is done for flight critical cases, with satellite`s solar panel pointing towards to the Sun. The polar orbit configuration has been evaluated. Two configurations of attitude controls, spin and 3-axis stabilizations, have been analyzed. 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 the Technological Institute of Aeronautics (ITA) in collaboration with other Brazilian universities, with technical support provided by National Institute for Space Research (INPE) and sponsored by Brazilian Space Agency (AEB). The commercial program SINDA/FLUINT has been used as a 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 of calculating the internal heat loads derived 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 studies it will be possible to calculate the temperature distribution in the satellite associated to these loads with the internal heat dissipations of the equipment. This study is part of the thermal control project that will guarantee 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 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 principle forms of environmental heating on orbit are sunlight, both direct and reflected from 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 undergraduates 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 external heat loads predictions for the ITASAT. The flight critical cases, hot and cold ones, have been simulated to evaluate the incident heat flux. A good compendium of technologies, thermal modeling and thermal data can be found in Gilmore (1994) and Baturkin (2004) Data reported by Leite (1986) and Abouel-Fotouh *et al*. (2006) have been used to validate the model.

1.1. ITASAT satellite

ITASAT satellite does not have yet a final defined configuration (March, 2010). 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: polar, approximately 600 km of altitude. 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.

To help in the definition of the future steps of the ITASAT program, two configurations have been analyzed in this work: spin-stabilized and 3-axis stabilized. In spin-stabilized configuration, the satellite will spin around its own "Z" axis, with approximately 40 rotations per minute. In 3-axis stabilized configuration, the satellite`s solar panel points towards to Sun during all time of the orbit. The satellite's pictures are shown in Fig. 1.

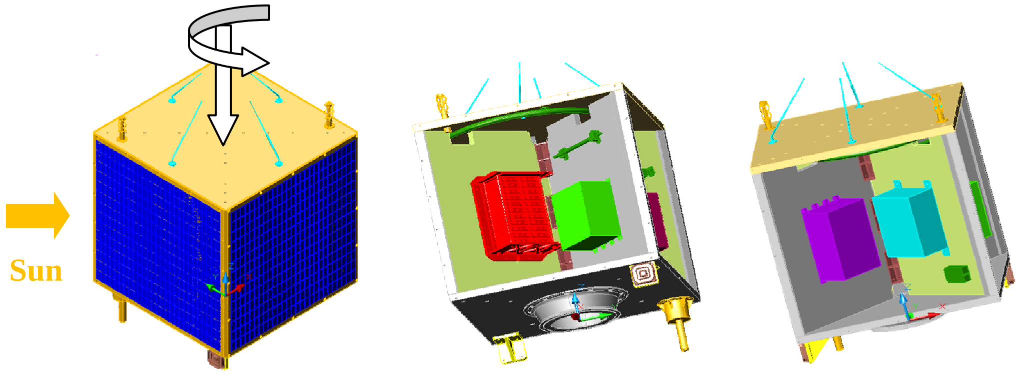

Figure 1. ITASAT's structure.

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 equipments, 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 on the lateral panels of the satellite, and the internal panels may be 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 equipments 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 equipments. 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 and low Earth orbit collaborate to obtain the temperatures inside the limits employing only passive thermal control materials. The TCS concept for the ITASAT satellite should be similar to that utilized in the SCD-1 satellite, where only this kind of 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 below. 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 condition and apply it in a surface in order to have simultaneously a high reflectivity in the solar spectrum and a 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 the 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 but 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. However, the intensity of IR energy, emitted at any given time from a particular point on the Earth, 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 CHARACTERISTICS

Environment fluxes must be known to calculate the normal incident fluxes that contribute to the heating of an orbiting satellite. Also, orbit dates, inclination, eccentricity, elevation, and satellite surface orientations with respect to the sun and Earth are needed for this calculation. 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 known as beta angle, β, defined as the angle that 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 passes 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 as a function of the orbit altitude, eclipse time drops to 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 orbit inclination is about 98 °.The variations of the beta angle are shown in Fig. 2.

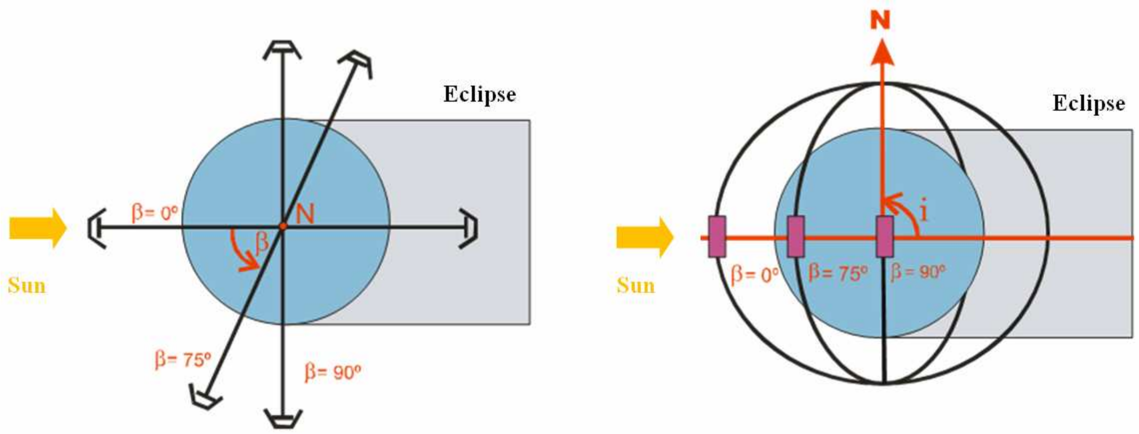

Figure 2. Different values of beta angle when seen from North Pole and Equator (Schelckle, 2008).

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.

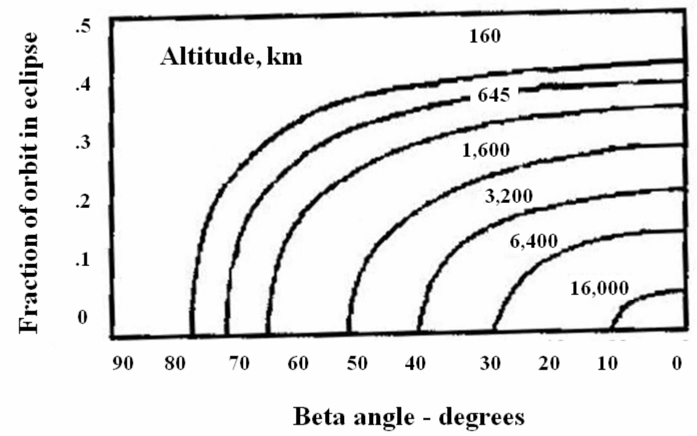

Figure 3. Eclipse durations (Gilmore, 1994).

3.1. Hot Case and Cold Case

To contend with errors, tolerances, and spacecraft uncertainties, thermal engineers almost universally adopt hot case and cold case 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 such way that 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	-58 °	-90 °
Solar radiation	1300 W/m²	1400 W/m²
Albedo	40%	40%
Earth radiation	198 W/m²	274 W/m²
Eclipse time	1290.5 s	0 s

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 calculation, resulting on temperature distribution, making the orbit sketch and allowing the satellite geometry assembly utilizing AutoCAD's environment.

Thermal Desktop™ is a code 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. RESULTS OF THE SIMULATION

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 it 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 fluctuations are 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, in spin-stabilized configuration.

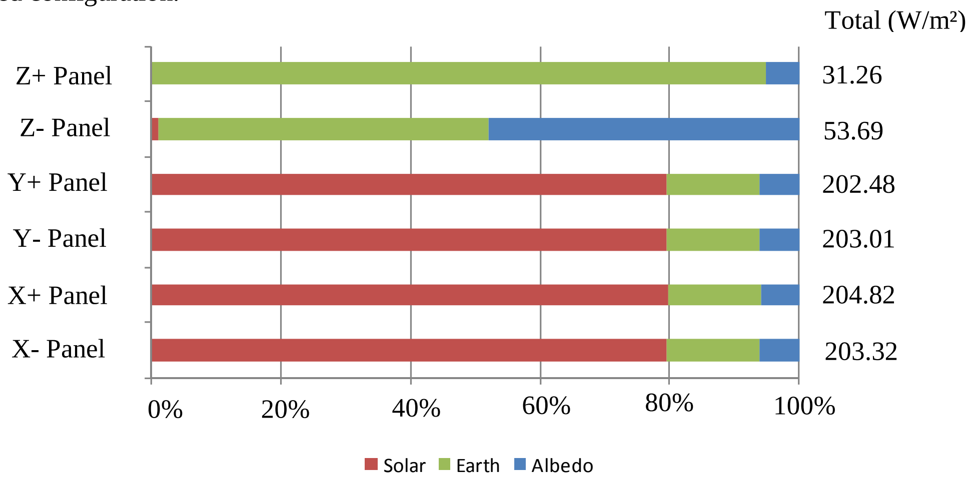

Figure 4. Percentage of incident heat flux for the cold case in spin-stabilized configuration.

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.

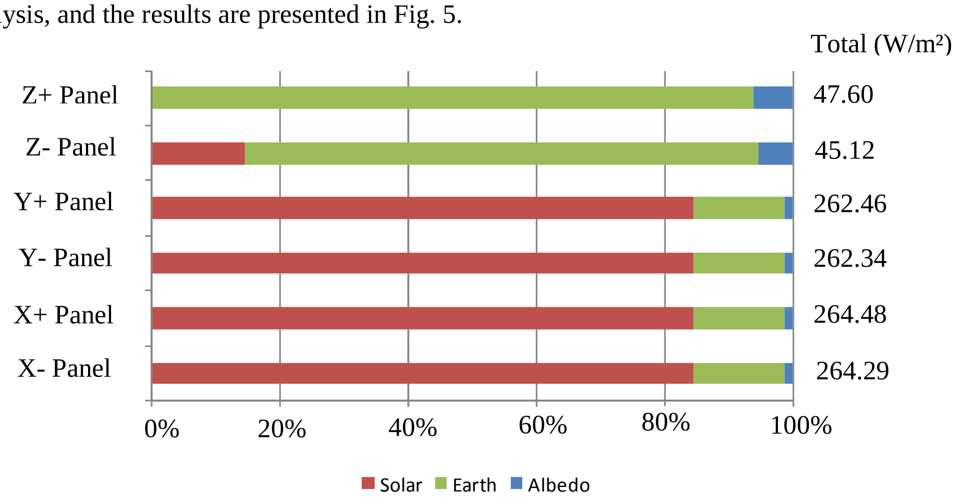

Figure 5. Percentage of incident heat flux for the hot case in spin-stabilized configuration.

The variations of the external total incident heat flux (solar, albedo and Earth) as a function of time, for cold and hot case conditions, for spin-stabilized configuration are presented in Fig. 6. The picture positioned at left is related to the cold case, and the pictured placed at right corresponds to the hot case analysis.

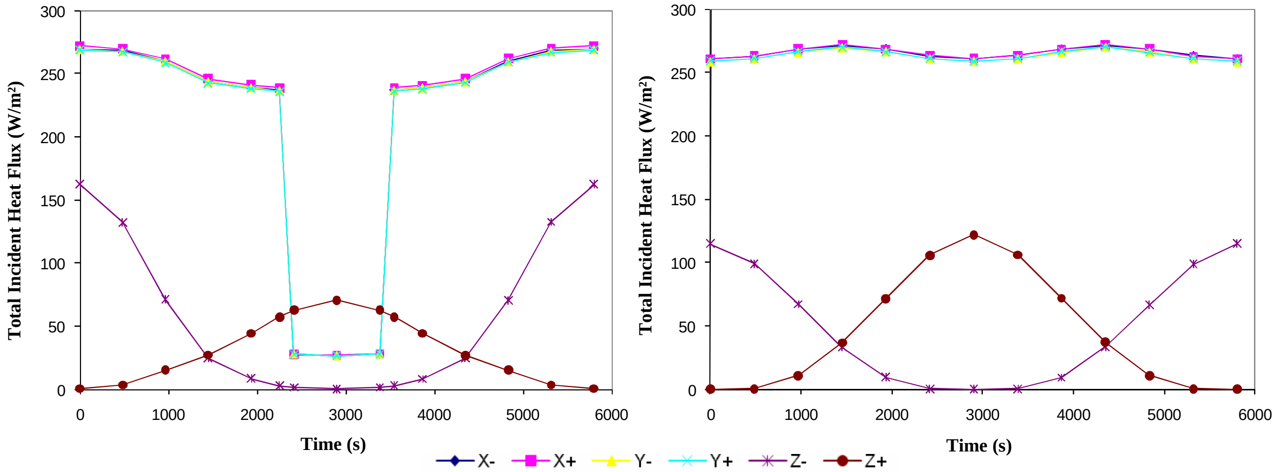

Figure 6. Total incident heat flux variation in spin-stabilized configuration.

By analyzing Fig. 6 it should be noted that the intensity of the total incident heat flux is similar for all lateral panels (panels X-, X+, Y- and Y+). In the picture positioned at left (cold case), the intensity of the total incident heat flux on the lateral panels decreases in the eclipse time (there is no solar radiation), and in the picture placed at right, the intensity on the lateral panels is uniform during all orbit time.

The results related to the 3-axis stabilized configuration are presented in Figs. 7, 8 and 9. In the 3-axis stabilized configuration, only one solar panel is pointing to Sun during all orbit time, resulting in high values of the incident heat flux to this panel. Figure 7 presents the incident heat flux percentage for the cold case, in 3-axis stabilized configuration.

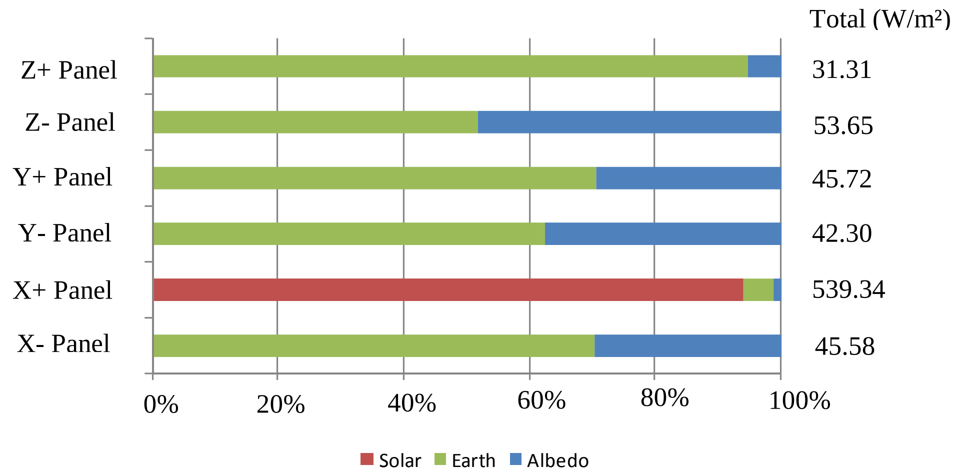

Figure 7. Percentage of incident heat flux for the cold case in 3-axis stabilized configuration.

As presented in Fig. 7, only one panel of the satellite (X+ panel) is being affected by the solar radiation, and the intensity of this solar radiation is significant in comparison with the others external sources. The same behavior occurs for the hot case analysis with the 3-axis stabilized configuration, as presented in Fig. 8.

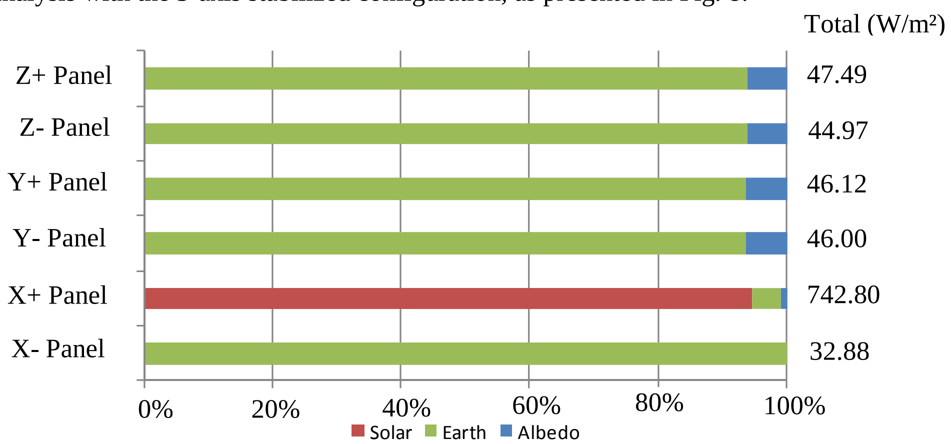

Figure 8. Percentage of incident heat flux for the hot case in 3-axis stabilized configuration.

The variations of the external total incident heat flux (solar, albedo and Earth) as a function of time, for the cold and hot case conditions, for 3-axis stabilized configuration are presented in Fig. 9. The picture positioned at left is related to cold case, and the pictured placed at right corresponds to hot case analysis.

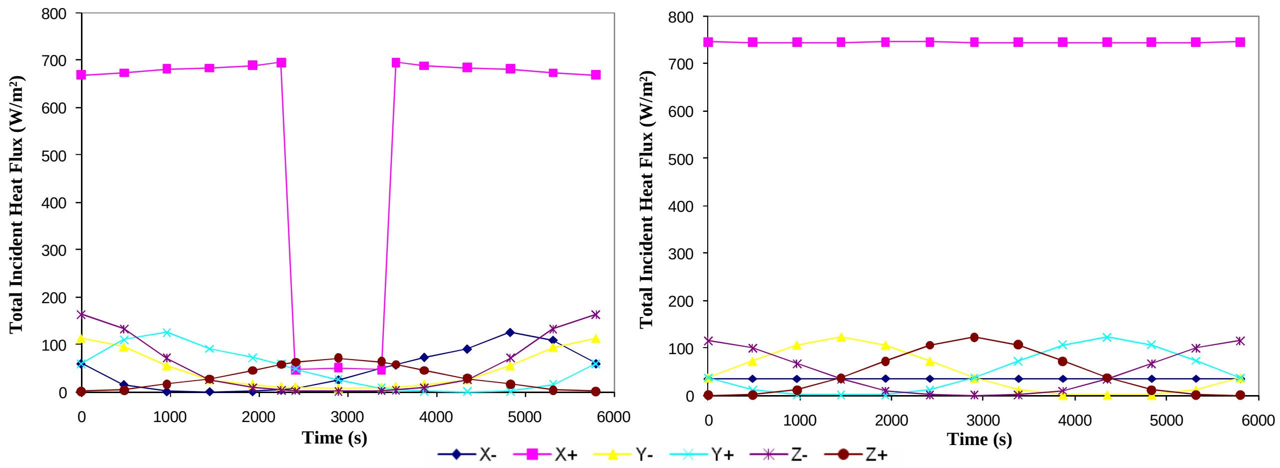

Figure 9. Total incident heat flux variation in stabilized configuration.

By analyzing Fig. 9 it should be noted that the intensity of the total incident heat flux is similar for all panels (panels X-, Y-, Y+, Z- and Z+) that are not affected by the solar radiation. In the picture positioned at left (cold case), the intensity of the total incident heat flux on panel X+ decreases in the eclipse time (there is no solar radiation), and in the picture placed at right, the intensity on all panels is uniform during all orbit time.

5. CONCLUSIONS

For that previous analysis, the values obtained for the total incident heat flux are normally expected for a spin-stabilized and 3-axis stabilized satellite, with low Earth orbit. As expected for a spin-stabilized satellite, the incident heat flux has almost the same intensity for all lateral panels, and the major source of heat is the solar radiation. For the case of 3-axis stabilized, where only one panel is pointing towards to Sun, this situation requires a detailed analysis in the future, because this type of configuration results on greater temperature gradients in comparison to that of the spin-stabilized. 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 transient condition can be obtained. These simulations have the purpose to provide initial information for thermal design and to help in the definition of the kind of attitude control to be adopted in the ITASAT program.

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.

Baturkin, V., 2005, “Micro-satellites thermal control - concepts and components”, Acta Astronautica 56, pp 161-170.

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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