X Workshop em Engenharia e Tecnologia Espaciais
7 a 9 de agosto de 2019

In-flight OSR Degradation Experiment Preliminary TMM Validation

ROQUE, R. S. [1]**, COSTA, R. L., VLASSOV, V. V.**

National Institute for Space Research (INPE), São José dos Campos, SP, Brasil
[1]Mastering Student in Space Mechanics and Control - CMC.

rafael.roque@inpe.br

Abstract. *Thermal control is the subsystem responsible to manage spacecraft heat in order to keep its components in operational conditions, despite the harsh orbital environment related temperatures. Radiators are control elements capable of rejecting excess heat directed towards deep space, which is possible due to special coatings installed on its surface. OSR is a promising coating family for this application, with huge advantages such as power savings. To be effectively used in radiators, OSR degradation curves need to be obtained via in-flight experiment. By its turn, it is useful to build a representative numerical model of this experiment to test smoothing algorithms. A preliminary experiment validation of this model in steady state was done and promising results verified. Further adjustments due to some complex heat pathways observed are still necessary and may well be complemented by transient analysis.*

Key words: thermal control; temperature; radiators; coatings; heat.

1. Introduction

The thermal control subsystem is the responsible for heat management and consequent temperature regulation of all satellite components, which shall be kept within specified limits.

In orbital conditions, the satellite is exposed to a hostile thermal environment, rejecting heat to deep space and being influenced by direct solar radiation, reflected solar radiation by Earth (albedo), and terrestrial emitted infrared radiation (IR). These heat exchanges occur exclusively by radiation once there is no air to allow convection, differently from what is observable in ground applications. Figure 1 illustrates those relations.

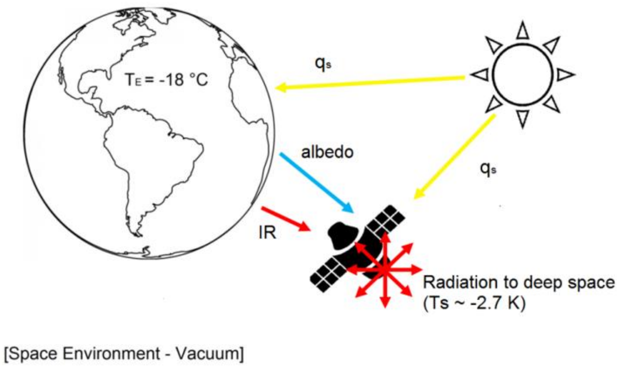

Figure 1. Usual thermal environment in the space.

Considering that radiation heat exchange is in general of relatively weaker intensity, it is necessary to optimize control components which allow reasonable heat management.

One head type of component is the radiators, which work as a thermal communication window between the vehicle and space. Through them, excess heat is rejected towards the exterior.

The space radiators make use of radiation physical phenomenon in order to reject energy to the space environment. Radiation is a heat transfer mode based on emission of energy by electromagnetic waves.

External heat fluxes affect heat rejection capability of the radiator. The net steady state issued power, Q_{out}, rejected from a radiator may be calculated using the Stefan-Boltzmann radiation law for grey bodies considering undesirable heating from external sources:

$$Q_{out} = \varepsilon \sigma T^4 A - q_s A - q_a A - q_{IR} A \quad [1]$$

Where A is the radiator area, ε is the surface emissivity and σ the Stefan-Boltzmann constant.

Figure 2 shows schematically the simplest and most used kind of radiator: consists of a cut window in the thermal insulation blanket, exposing a region of the honeycomb structural panel. This exposed area should be dimensioned and coated with an adequate set of thermo-optical properties, which should make it thermally efficient. Regarding a fully passive equipment variation, it is generally cheaper, easier to manufacture and highly reliable.

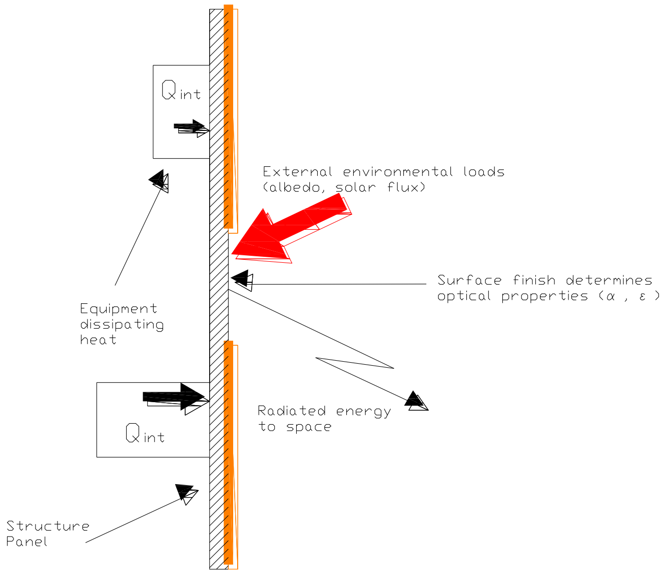

Figure 2. Simple radiator mounted in a satellite panel.

Usually, an efficient radiator device is the one capable of emitting the highest possible energy without absorbing much of the incident external heat loads. In other words, it is a radiator in which the energy flux has a preferential well-defined direction. However, the capability of a surface to absorb irradiated energy in a given wavelength λ is characterized by its absorptivity α_λ in the respective wavelength, which is in turn equal to the surface's capability of emitting radiation in this wavelength, referring to Kirchhoff's law, $\alpha_\lambda = \varepsilon_\lambda$.

In the specific case of satellites, the preponderant external heat source comes from solar radiation. Fortunately, the Sun's characteristic temperatures and those observed in spacecraft parts in orbit are hugely different. Regarding this fact, black body theory says that in this case higher incident and emitted power densities are verified for very different wavelengths too [Messeguer *et al*, 2012]. As a result, thermal radiation emitted by the radiator is predominantly in IR band, meanwhile Sun's emitted radiation has strong intensity in UV and visual band [Bergman e Lavine, 2017], as shown in Figure 3.

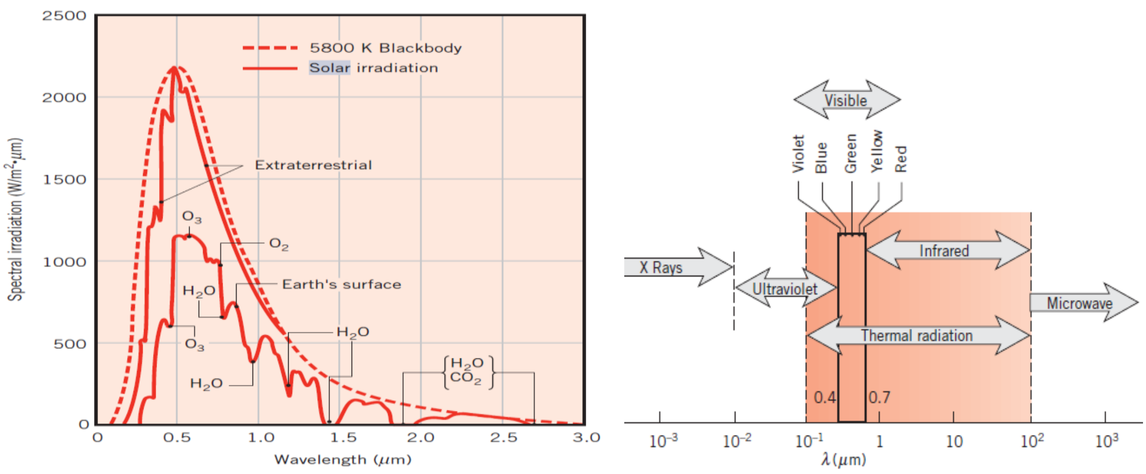

Figure 3. Solar radiation spectra in Earth's orbit. Adapted from Bergman and Lavine (2017).

Using this particular relation between internal and external heat sources, attempts are made for covering the radiator's area facing space by using materials with high emissivity in IR (ε_{IR}) and low absorptivity in solar spectrum (α_s). The radiator efficiency is strongly related to the $\alpha_s/\varepsilon_{IR}$ ratio observed in its coating. White paints, such as Chemglaze A276 and CR107, have those properties and have been widely used in radiator assemblies, including in CBERS and Amazonia satellite programs. Easily built, radiators which make use of white paints have the advantage of lower manufacture complexity. Nonetheless it is related to the inconvenient of high degradation rates causing expressive α increases throughout mission progress.

Factors like erosion caused by residual atmosphere, UV degradation of polymeric chains of the materials paints are made of, chemical interaction with volatiles condensed in the radiators [Karam, 1998], among others have the potential to double absorptivity until end of life (EOL) is reached [Jaworske and Kline, 2008]. This increase in α reduces radiator efficiencies considerably.

The radiators need to be effective in the hottest thermal scenario, represented by the maximum thermal loads combination and absorptivity in EOL. If conceived for materials which behave as white paints, in mission first stages the radiators reject more energy to space than desired and impose colder temperatures to spacecraft components as consequence. This provokes the necessity of reheating the components resistively, but this has to be done considering power budged limitations. Besides, using heaters increase system's complexity and reduce thermal control reliability.

On the other hand, Gilmore *et al* (2002) report experiments in which good stability has been observed for low absorptivity α in samples of materials known as Optical Solar Reflectors (OSR). In essence, OSR are mirrors built using thin vapour deposited metal films over borosilicate substrates. The manner they are installed in radiators allow then to be considered Second Surface Mirrors (SSM), because the reflective layers in kept protected by its substrate. An usual configuration is presented in Figure 4.

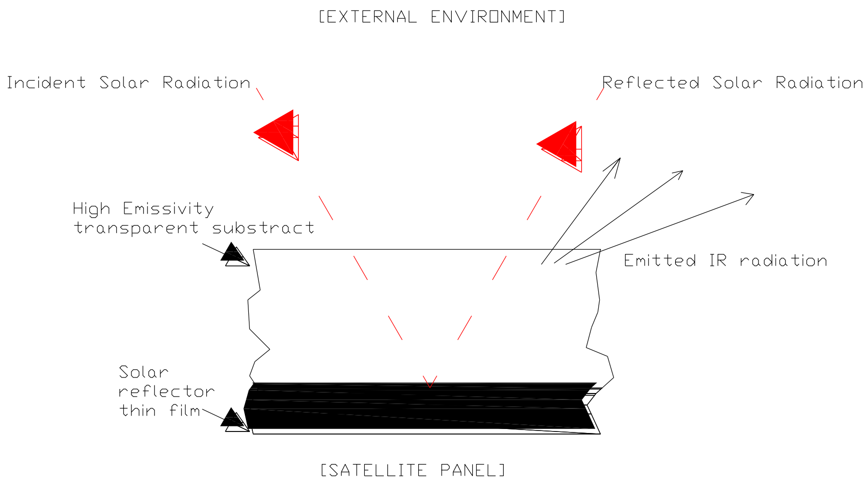

Figure 4. Second Surface Mirror (SSM).

OSR coatings adoption allows obtaining radiators with minimum area closer to ideal for all mission phases and more stable thermal conditions likewise.

Although its advantages, OSR manufacturing by thin film deposition processes is affected by high variability. To cope with this problem, some film compositions have been investigated previously at INPE [Boato *et al*, 2017] as well as the respective manufacturing processes.

The most promising layer combination found, which is made of Aluminium, Silver and Chrome, was subjected to qualification procedures. Those samples have been subjected to standard qualification tests, such as vibration, ambient thermal cycling, vacuum thermal cycling and thermal shock, with general good behaviour observed. Their final step into the complete validation is the on-orbit test.

Finally, a technological experiment has been designed to part of the CBERS 04 A satellite that will be launched on December 2019. Such experiment aims to observe the Brazilian OSR samples performance and degradation during the satellite mission. This information will be indirectly evaluated by the use of temperature telemetry data, Figure 5.

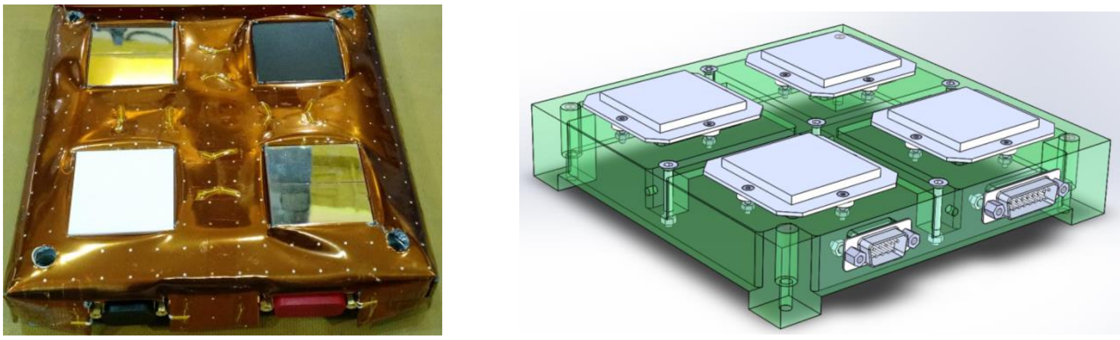

Figure 5. OSR degradation experiment assembly and its mechanical model.

As observed in the Figure 5, the experiment consists of a box equipped with 4 isolated sample holders made from aluminium with heaters and thermistors attached on the inside. This assembly is positioned in Z- face of the satellite, pointing towards zenith and without any exposure to albedo. It is also thermally protected by multilayer insulating blanket (MLI) mounted over its entire external surface, except over the samples, which are kept exposed to space environment.

Among the 4 sample holders available faces for specimen installation, two of them will be occupied by OSR samples developed in INPE with degradation behaviour to be measured, one by a reference black anodized surface with highly stable optical properties and the last one by white paint with well-known and documented degradation behaviour. Heater and thermistor are placed back side of the aluminium samples; their positions are schematically shown in Figure 6.

Figure 6. Heaters and thermistors placed inside the experiment assembly.

It is intended to obtain absorptivity α value alterations with mission time indirectly of the samples from in-flight temperature data. The basic transient thermal balance for each sample can be generally described by the following equation:

$$C_m \frac{dT}{dt} = Q_{heater} + \alpha q_s A + G_L\left(T_{ref} - T_{sample}\right) - \varepsilon\sigma T^4 A \qquad [2]$$

Where C_m is sample's thermal capacitance, $q_s$the heat flux in solar spectrum, A the sample's area, $G_L$the parasitic thermal coupling between sample and a reference and$\left(T_{ref} - T_{sample}\right)$the temperature difference between reference and sample.

Notably, the inversion of equation 2 reveals that surfaces' absorptivity depends on the temperature to the forth power, which means that a simple data substitution is very vulnerable to measurement noise. Therefore, there is a need for the development of a data treatment algorithm for smoothing. This algorithm may use the know boundary and tie conditions.

Moreover, the configuration of the experiment is relatively complex, therefore a mathematical model based on the system of differential equations like (2) may not provide all necessary details of multiple heat transfer links on interior of the experimental box. More refined numerical model, which represents detailed geometry of the experiment configuration is needed.

In this scope, a numeric model of the experiment had been developed, which represents geometry and interface thermal contacts detailed, as well as the boundary conditions. In order to perform a preliminary adjustment in TMM, test data from CBERS 04 A Thermal Balance Test (TBT) has been compared with numerical calculations. Finer adjustments will be done in the future using data as well from a specific TBT for the experiment alone mounted with final flight samples.

2.Thermal Mathematical Model (TMM)

A detailed TMM had been built for the OSR degradation experiment, in order to make precise temperature figures easier to obtain. This level of resolution is important because small temperature divergences can reflect in big noises for calculatedα. The referred TMM in depicted in the Figure 7.

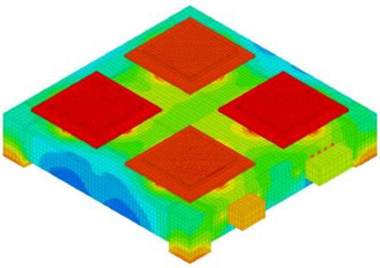

Figure 7. Experiment's TMM with temperature map relative to an arbitrary condition.

The low inherent thermal capacitance contributes to increase secondary thermal routes relevance, for example through cables, and therefore sums up the necessity for TMM detailing.

It is understood for detailed model the numerical representation which had been build using: more elaborate part geometries, closest to real (which has gaps, reinforcements, grooves, etc.); higher nodal resolution; separated geometrical representation for MLI blanket; segmented interfacial contacts depending on the fastening technique employed; addition of appendices geometries representations as sensors, washers, bolts, to cite a few.

Taking into account that contact parameters and thermo-physical properties have been defined based on robust data available in the literature, added to previous tests executed in INPE, the numerical model still needs to be adjusted and validated. For this reason, CBERS 04 A TMM's thermal data relative to the experiment had been acquired.

Recently, a TBT test was performed on the CBERS 04 A satellite, where OSR experiment has been installed. The satellite was tested under most cold and hot conditions, and the OSR heaters have been switched ON and OFF during the test. The obtained temperature measurements were recorded by Data Acquisition Systems and are available to use for the OSR model adjusting. For this purpose, the numerical model shall reproduce the vacuum chamber heat ambient conditions used during the satellite testing.

The satellite TBT boundary conditions were reproduced in the model in order to allow model-test temperature comparison. If any divergences are observed, modifications are possible in order to adjust data and should begin on the hardest parameters todetermine theoretically, as are some thermal contact interfaces. In the case of implausible modifications are needed for data adjustment, useful indications can be extracted like when nodal layout reconfiguration is needed or problems with test acquisition are identified.

3. Results and Discussion

The model has shown very promising behaviour with reduced differences for temperature levels in steady state when compared to experimental dataset. This is especially true when heaters were maintained on: samples evolved to an average of 258 K experimentally while 257 K is the approximate temperature for their numerical counterpart. In both situations, temperature mean deviations were smaller than 2 K. Therefore, when the thermal loads are applied the difference between experiment and TMM is less than 0.4 %.

In the other hand, when heaters were off all samples evolved to 208 K on CBERS TBT. This is not the case for its numerical representation, which developed higher temperatures: samples closer to connectors gravitated 230 K whereas those positioned opposite kept around 224 K. Unfaithful conductance intensity for thermal couplings between FR4 box and satellite panel though connectors are probably the source of this divergence. The mechanical complexity of connectors makes their thermal properties highly anisotropic and challenging to predict. A temperature map is represented in Figure 8 for heaters on and off scenarios.

In the numerical model, negligible temperature differences were obtained between both OSR samples. This phenomenon is compliant with figures of temperatures that could be verified experimentally.

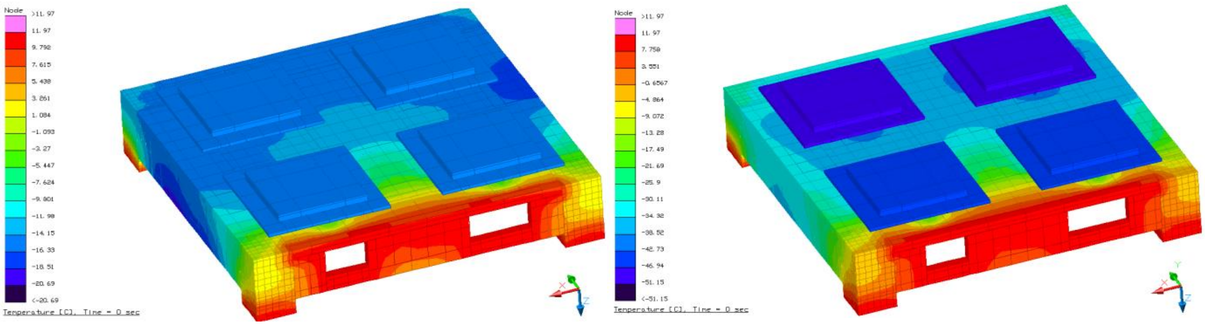

Figure 8. TMM temperature maps for heaters on and off conditions, respectively.

4. Conclusion

It is believed that there are considerable divergences of thermal conductor intensities, which are mainly related to couplings created by wire setup. Numerical model has shown sensitivity to wire heat paths, which suggests that wire routes inside the experiment should be reviewed alongside connectors' properties. Currently transient cases are being computed to refine this setup, which will allow deeper analyses in the future.

Acknowledgement: *To the Coordination for Higher Education Level Staff Improvement (CAPES) for the given financial support to this work.*

References

Bergman, T. L., Lavine, A. S. (2017). Fundamentals of Heat and Mass Transfer, Hoboken: John Wiley & Sons, 8th edition.

Boato, M. G., Garcia, E. C., Santos, M. B., Beloto, A. F. (2018) Assembly and Testing of a Thermal Control Component Developed in Brazil. In Journal of Aerospace Technology and Management, São José dos Campos, v.9, n. 2, p. 240-258.

Ganji, D. D., Sabzehmeidani, Y., e Sedighiamiri, A. (2018). "Radiation Heat Transfer". In Nonlinear Heat Transfer: mathematical modelling and analytical models, Cambridge: Elsevier, p. 105–151.

Gilmore, D. G. (2002)."Radiators". In Spacecraft Thermal Control Handbook – volume 1, Edited by Gilmore D. G., El Segundo: The Aerospace Press, 2nd edition.

Gilmore, D. G., Stuckey, W. K., Fong, M. (2002). "Thermal Surface Finishes". In Spacecraft Thermal Control Handbook – volume 1, Edited by Gilmore D. G., El Segundo: The Aerospace Press, 2nd edition.

Jaworske, D. A., Kline, S. E., Review of End-of-Life Thermal Control Coating Performance. Report: NASA/TM-2008-215173 . Disponível em : <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080018585.pdf>. Accessed in 15 jun. 2019

Karam, R. Satellite Thermal Control for Systems Engineers. Reston: American Institute of Aeronautics and Astronautics (AIAA), 1998.

Zhang, Y., Li, Q., & Zhou, H. (2016)."Emission and Absorption of Thermal Radiation". In Theory and Calculation of Heat Transfer in Furnaces, London: Academic Press, p. 45–74.