THERMAL PROBLEMS ASSOCIATED TO THE ASCENT PHASE OF STRATOSPHERIC BALLOON PAYLOADS. THE SUNRISE MISSION

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ABSTRACT

SUNRISE is a solar telescope flown with a NASA LDB (Long Duration Balloon) stratospheric balloon. Its aim is to observe structures on the Sun with a resolution never previously achieved. The design of the thermal control of SUNRISE has been critical, for being the opto-mechanical devices as well as the electronics very sensitive to temperature. This work is focused on the thermal study of a generic payload carried by a long duration balloon during the ascent phase. A model taking into account convective and radiative thermal interactions has been set up. The payload's temperature has been obtained as a function of the altitude from ground to floating conditions. The results have been correlated with measurements taken during SUNRISE test flight.

1. INTRODUCTION

SUNRISE is an international project led by the Max Planck Institut für Sonnensystemforschung (MPS, Lindau, Germany) with the participation of other european and american institutes such us KIS (Freiburg, Germany), HAO-NCAR (Boulder, USA), IAC (Tenerife, Spain), IAA-CSIC (Granada, Spain), INTA (Madrid, Spain), GACE (Valencia, Spain) and IDR-UPM (Madrid, Spain).

The solar telescope SUNRISE was launched on June, 8th, 2009 from the launch site at Esrange Space Center, a facility of the Swedish Space Corporation. The launch was successfully conducted by the NASA CSBF (Columbia Scientific Balloon Facility) team. After almost six days of flight at a floating altitude of about 37 km, it landed on Somerset Island, in northern Canada. This almost constant latitude trajectory allows in this season permanent Sun observation. With a primary mirror of 1 m in diameter, a filtergraph (SUFI) for high-resolution images in the visible and UV spectral ranges, and a magnetograph (IMaX) providing two-dimensional maps of the complete magnetic field vector and the line-of-sight velocity, SUNRISE has obtained images with an unprecedented resolution in a spectral domain not accessible from ground. A picture of SUNRISE and the balloon already inflated and ready to be launched at Esrange balloon pad facility can be seen in Fig. 1.

Aiming to test the pointing system, to verify and validate the thermal design and to check the correct operation of other devices of SUNRISE, an engineering test flight was conducted on October, 3rd, 2007. For this test flight the telescope and part of the equipment were replaced with dummies with the same mass properties as those used in the science flight. The balloon was launched by the NASA CSBF team from Fort Sumner (New Mexico, USA) reaching a float altitude of about 37 km. The duration of the ascent phase was about 2 hours and 20 minutes.

Figure 1. SUNRISE ready for launch at Esrange launch pad.

As it happened for SUNRISE test flight, the ascent phase of stratospheric balloons usually takes less than three hours, quite a short period compared to the duration of the whole mission. For this reason, thermal analyses carried out during the development phase of this type of projects are usually focused on the cruise phase rather than on the ascent phase. However, although this initial period of the mission is short, payloads are subjected to very harsh conditions due mainly to the convective cooling through the cold

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atmosphere, with minimum temperatures in the tropopause.

Particularly, during SUNRISE test flight, environment temperatures much lower than expected were found during such ascent phase. Values of −70ºC, more than 15ºC below the values of the Standard Atmosphere provisions, were measured at an altitude of about 15 km, with the subsequent cooling of equipment beyond the acceptable limits.

In order to predict the thermal behaviour of a generic electronic box during the ascent phase, a thermal model of a single box has been set up. Thermal loads onto the system have been calculated as a function of the altitude, of the environmental conditions (which also depend on the altitude) and of the own system temperature.

The resulting differential equations have been solved to determine the temperature as a function of the altitude. The results obtained with the model have been compared with measurements during SUNRISE test flight.

2. THERMAL MODEL

The model here analysed consists of one electronics box with a given internal dissipation mounted on a flat surface of the gondola.

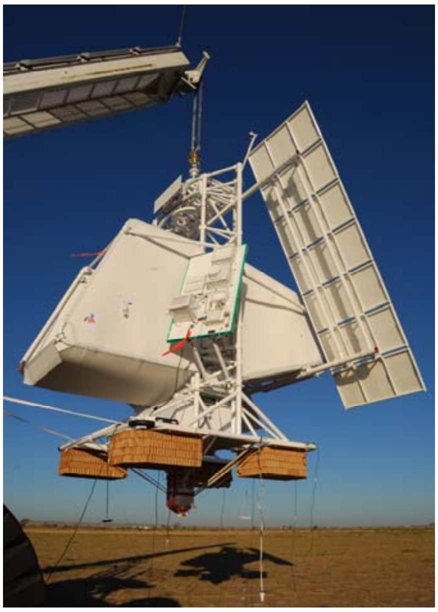

Figure 2. SUNRISE test flight configuration ready for launch.

This model would represent any of the boxes mounted on one of the electronics racks of SUNRISE, as shown for the test flight configuration in Fig. 2.

So the configuration here analysed consists of a box attached to the side of the gondola as is shown in Fig. 3. The area of the front face of the box is A. This is the area considered to be exposed to outer radiation and convection. During the ascent phase of the balloon, it has been considered that the gondola rotates around its vertical axis.

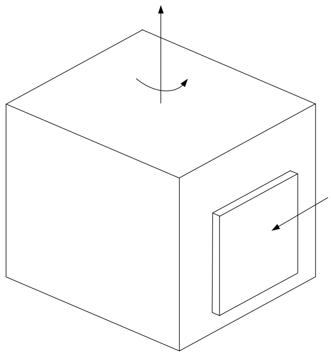

Figure 3. Sketch of the electronics box on the gondola

The model consists of two nodes: the housing of the box or outer node 'o' and the inner dissipating node 'i', here called chipset. The energy equation for each of these two nodes can be written as:

$$\begin{aligned} m_i c_i \frac{dT_i}{dt} &= P_{\text{dis}} + C_{ij}\left(T_j - T_i\right) \\ m_o c_o \frac{dT_o}{dt} &= \dot{Q}_{net} + C_{ij}\left(T_i - T_j\right) \end{aligned} \qquad (1)$$

where m is the mass, c is the specific heat capacity, T is the temperature, t is the time, P_{dis} is the power dissipated and $\dot{Q}_{\text{net}}$ is the net heat transfer onto the box surface. The term C_{ij} represents the thermal coupling between the inner and outer node.

The thermal loads on the box, the radiative and convective interactions, depend on the temperature of the surface, on the temperature and pressure of the surrounding air and on the altitude. To solve the equation all these thermal loads have been calculated as a function of the altitude. The relation between the altitude H and the time t is obtained assuming that the ascent velocity of the gondola v is constant and therefore: $H = v\ t$. This assumption has been verified with flight data.

The radiative thermal interactions consists of the direct solar radiation, the solar radiation reflected on the balloon surface, the solar radiation reflected on Earth, that is, the albedo, the infrared radiation from Earth and the own emission of the surface. To evaluate the convective interactions, a heat transfer coefficient for forced convection dependent on the Reynolds number has been estimated. More detailed information about the procedure of calculation of all the thermal loads necessary to evaluate the right-hand terms in Eqs. 1 can be found in [1].

3. RESULTS

The model described above has been applied to one of the electronics boxes operational during the SUNRISE test flight: ICU. This box was instrumented with several thermocouples to monitor its temperature. Particularly, the housing and the chipset were monitored. The data provided by these two sensors have been used for the comparisons. The box outer surface is painted with white paint, so that $\alpha = 0.23$ and $\varepsilon = 0.85$ have been used as thermo-optical properties of the outer surface for the determination of the external radiative thermal loads.

Equations 1 have been applied to this system: to the housing of the box, where all external loads are applied, and to one inner chipset, where the internal dissipation is applied.

To calculate all the thermal loads dependent on the environmental conditions, atmospheric measured temperatures have been fit with linear functions. So, the atmospheric temperature profile has been considered as two linear sections; each one fits the data corresponding to each of the two constant temperature rate changes that it has been seen the ascent phase consists of. Pressure measurements (necessary to compute air density and the convection heat transfer coefficient) have also been fitted to analytical expressions.

The conductive coupling between the inner node and the housing node has also been taken into account in the calculations, in such a way that both equations are coupled. The coupling coefficient between nodes has been determined from the measured data.

The set of two differential equations (Eq. 1) has been solved (using a Runge-Kutta fourth order method) to obtain both temperatures as a function of the altitude. These results are presented in Fig. 4. For comparison, in this figure, apart from the calculated values, measured values are also presented. Atmosphere temperatures, measured and linear approaches are also plotted. As has been said in previous Sections, and can be checked in the figure, atmospheric temperatures lower than the provided by the Standard Atmosphere have been measured.

Unfortunately, during the ascent phase of the test flight, one of the computers stopped working and in flight data were not recorded for a period of time. The system was restarted practically at float altitude. This is why experimental data are not shown as continuous plots in Fig. 4.

In Fig. 4, it can also be seen that, once adjusted the model parameters, when comparing the experimental data with the calculated temperatures from the model both match really well. Differences between both values are higher in the second phase of the ascent, but in any case they keep below 5ºC.

Although the thermal behaviour of the system at float altitude was as expected, in the figure it can be seen that convection affects significantly the thermal behaviour of the box during the ascent phase, cooling it under the admissible limits.

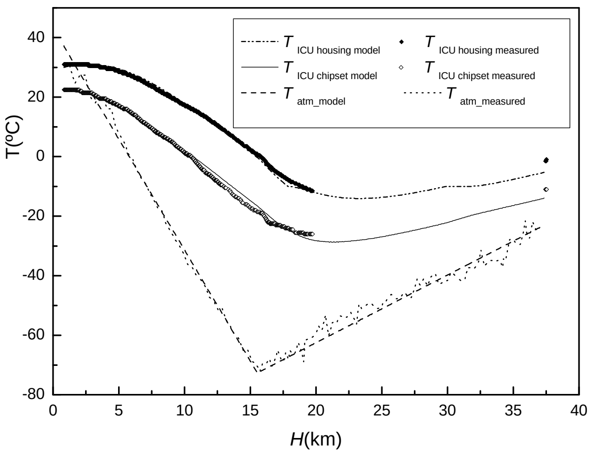

Figure 4. Temperature, T, versus altitude, H, of the box housing and inner chipset (measured and model results). Atmospheric air temperatures (measured and linear approach) are also indicated.

4. CONCLUSIONS

When carrying out thermal analyses of balloon payloads, although short compared with the whole mission, the ascent phase requires a dedicated thermal analysis for it being one of the worst case cold conditions the payload could find.

In this work, a model to study the thermal behaviour of a generic balloon payload during the ascent phase has been developed. These simple analytical models are very useful at the beginning of the mission definition, that is, when the design is not still closed. They also facilitate to carry out parametric studies. Relevant parameters for the thermal design are this way also easily identified.

Flight measurements have clearly shown that atmospheric temperatures can be lower than expected and therefore, the design has to be conservative in this way.

From SUNRISE test flight data it can be seen that the convective cooling during the ascent phase could lead the equipment to temperatures lower than the admissible ones. Therefore, the use of convective shields for equipment exposed directly to ambient air is recommended. This way the devices are prevented from direct convective cooling. This has already been done for SUNRISE science flight electronics and the temperatures monitored during the ascent phase seem to have been kept within the allowable range.

In the moment of writing this paper, the data storage system of SUNRISE science flight has just been recovered. As soon as the flight measurements recorded during the flight are retrieved, a thermal correlation with the model will be established in order to analyse the performance of the convection shield.

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