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Selection of extreme environmental conditions, albedo coefficient and Earth infrared radiation, for polar summer Long Duration Balloon missions

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ABSTRACT

The selection of the extreme thermal environmental conditions –albedo coefficient and Earth infrared radiation– for the thermal design of stratospheric balloon missions is usually based on the methodologies applied in space missions. However, the particularities of stratospheric balloon missions, such as the much higher residence time of the balloon payload over a determined area, make necessary an approach centered in the actual environment the balloon is going to find, in terms of geographic area and season of flight. In this sense, this work is focussed on stratospheric balloon missions circumnavigating the North Pole during the summer period. Pairs of albedo and Earth infrared radiation satellite data restricted to this area and season of interest have been treated statistically. Furthermore, the environmental conditions leading to the extreme temperatures of the payload depend in turn on the surface finish, and more particularly on the ratio between the solar absorptance and the infrared emissivity α/ε. A simple but representative thermal model of a balloon and its payload has been set up in order to identify the pairs of albedo coefficient and Earth infrared radiation leading to extreme temperatures for each value of α/ε.

1. Introduction

Long Duration Balloons (LDB) play a relevant role as relatively low cost alternative platforms for scientific experimentation, as well as potential platforms for the development and test of space technology. Reaching the stratosphere allows the observation of outer space practically out of the atmosphere. Moreover, in this type of mission the payload can be recovered after flight, which provides the user with valuable information about the performance of the instrument and also allows its reuse.

During the polar summer periods, the stratospheric winds are very stable from the east, which makes trajectories very predictable: the balloons are expected to circumnavigate the poles. This scenario is very favourable for astronomic observations where long measuring times are needed [1]. Furthermore, it allows permanent solar observation, LDBs then are ideal platforms for the study of the Sun out of the atmosphere [2,3]. The float altitude of an LDB is determined by the balloon volume (up to 40 MCF, or 1.13 million m^3) and the mass of the payload. LDBs can carry up to 2700 kg to an altitude ranging from 36 to 39 km. A typical duration of the mission in the North polar area is 7–15 days, although they could even reach 55 days in the South [4].

At float altitude, the ambient pressure is lower than 300 Pa, and therefore convective heat transfer is negligible in most systems. Thus, the thermal environment of a LDB is quite similar to the environment found in space by a spacecraft orbiting in a Low Earth Orbit (LEO). For this reason, the thermal design of balloon instruments is usually carried out in a similar way as it is done for space systems: bus and payload are designed for the worst-case (hot and cold) scenarios [5–7]. The definition of these dimensioning scenarios requires identification of the extreme environmental conditions that the system is going to encounter during the flight, namely, solar radiation, albedo flux and infrared radiation from Earth and the atmosphere, also called “outgoing longwave radiation” (OLR).

A deep analysis of these scenarios based on satellite measurements is presented in Ref. [8]. Data in Ref. [8] are taken from ERBS, NOAA-9 and NOAA-10. As is stated in the document, when defining the worst (hottest and coldest) environment, selecting the most extreme albedo coefficient, a, and OLR simultaneously would lead to an oversizing of the systems since it is not expected that both will occur at the same time. More particularly, using for the hot case the maximum albedo and the maximum OLR values would lead to radiators bigger than necessary, and using for the cold case the minimum albedo and the minimum OLR values would lead to heaters (and accordingly the power system) bigger than really necessary. The reason why both maximum or minimum values cannot be used simultaneously is the fact the pairs (a, OLR) are partially correlated in such a way that high albedo values tend

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Nomenclature

A	Area [m^2]
A_p	Projected area [m^2]
d_{G-B}	Distance between the gondola and the balloon [m]
$F_{i,j}$	View Factor of node i to node j
G_s	Solar irradiance [W/m^2]
h_B	Altitude of the balloon [km]
MCF	Million Cubic Feet
q_E	Radiative infrared flux emitted by the Earth, or OLR [W/m^2]
$\dot{Q}_{aB}$	Albedo radiation absorbed by the balloon [W]
$\dot{Q}_{aG}$	Albedo radiation absorbed by the gondola [W]
$\dot{Q}_{net_i}$	Net heat transfer onto the node *i* [W]
$\dot{Q}_{SB}$	Solar radiation absorbed by the balloon film [W]
$\dot{Q}_{SG}$	Solar radiation absorbed by the gondola [W]
$\dot{Q}_B^{IR}$	Balloon film emitted infrared radiation [W]
$\dot{Q}_G^{IR}$	Gondola emitted infrared radiation [W]
$\dot{Q}_{B_{int}}^{IR}$	Balloon inner infrared radiation absorbed by itself [W]
$\dot{Q}_{BG}^{IR}$	Balloon infrared radiation absorbed by the gondola [W]
$\dot{Q}_{EB}^{IR}$	Earth infrared radiation absorbed by the balloon [W]
$\dot{Q}_{EG}^{IR}$	Earth infrared radiation absorbed by the gondola [W]
T	Temperature [K]
α	Solar absorptance
ε	Infrared emissivity
θ	Sun elevation angle
ρ	Reflectance
ρ'	Effective reflectance
σ	Stefan-Boltzmann constant [W/m^2K^4]
τ	Transmittance

to be paired with low or moderate OLR values, and vice versa. For this reason, the classic method used to select the albedo coefficient and OLR pairs is based on the statistical analysis of satellite data [9]. The selection of the extreme cases is based on cutting the tails of the a and OLR data distributions, ± 3.3 σ for Gaussian distributions with a confidence interval of 99.9%. It is important to note that, even though the term 'probability' is used throughout the paper, these tails do not exactly represent the probability the values of a and OLR are expected to be exceeded over the mission, but the fraction of mission time the exceedance may happen. This requires a deep study of the time constant of the systems directly exposed to albedo and OLR in order to identify possible critical items.

Furthermore, the pairs (a, OLR) that lead to extreme temperatures depend not only on their own values, but also on the surface properties of the system: the solar absorptance α and the infrared emissivity ε, more particularly on the ratio α/ε. This makes the selection of the environmental conditions also a dynamic process, as it has to be updated as the design evolves, unless the ratio α/ε is frozen from the early stages of design.

Aware of the importance of the identification of the worst design scenarios in space missions, mainly in LEO missions, this topic is currently of interest for NASA [10] and ESA [11]. However, based on the considerations previously described, LDB missions present several particularities that make the methodology and results obtained for space missions not suitable to be applied directly.

First, the residence time of a balloon payload over a determined area is much higher than the residence time of a LEO satellite. An LDB following a circumpolar trajectory in summer flies towards the west at an average speed of about 30 km/h. Considering a typical float altitude of 40 km, this results in the system having an effective view of a local point during about 12 h (see Section 2.1 for more details).

Second, the data presented in Ref. [8] include values of pairs (a, OLR) for the whole Earth and for all time periods, whereas polar LDBs fly only over a very definite area and a mission lasts a few days. Therefore, data limited to the flown area and season should be considered. As already said, it is of great importance to identify in a realistic way the values of albedo and OLR where the distribution is to be cut, as they somehow represent the time fraction where the extreme values are going to be exceeded. Depending on their thermal capacitance, the time constant of units and structures on a balloon gondola can range from 30 min to 3 h (shorter, but not much shorter than the residence time).

Third, in these systems, the value of the ratio α/ε plays a crucial role in identifying the pairs (a, OLR) that lead to extreme conditions, and it has to be considered in the process.

And last, the payload has the balloon surface over it, at a distance of about 60 m, which means an additional surface of about 100 m in diameter, acting as a huge reflector for all the radiative interactions involved: solar, albedo and OLR.

Based on these points and on the fact that there is not a clear methodology to determine the worst environmental conditions for a stratospheric balloon payload, in this paper a deep study on this topic has been carried out for a LDB operating in the northern polar summer. The study starts with the analysis of local satellite data with high spatial resolution and detailed time evolution from NASA's Clouds and Earth Radiant Energy System (CERES) [12]. The data were retrieved just for the area and period of time of interest.

These data have been analysed and treated statistically to obtain an envelope of hot and cold environments in a realistic way, without being too conservative but also reducing the amount of data managed. By doing so, computational times are considerably reduced. This treatment opens up the possibility of a parametric sweep with a quite simple, but realistic, thermal model, set up just for this purpose. In this way, the pairs (a, OLR) leading to the hottest and coldest temperatures for each ratio α/ε have been obtained.

Although the methodology here shown is general, the paper is written in the context of the NASA Columbia State Balloon Facility (CSBF) summer campaign flights from Esrange (Sweden) to Canada. More particularly, in the context of the Sunrise missions, 1-m balloon-borne solar telescopes. Sunrise 1 was flown on June, 8th, 2009 [2], Sunrise 2 was flown on June 10th, 2013 [3], and Sunrise 3 is under development, expected to be flown in June 2021.

Needless to say that the coldest conditions for an LDB are those found during the ascent, due to the convective cooling during the pass through the tropopause. Nevertheless, for most astronomical and solar missions, this phase is not a science phase, and is usually thermally analysed in a separate way [13]. This paper is just focussed on the cruise phase of the balloon flight, once the floating altitude is reached.

2. CERES data

The starting point in the study presented in this paper are the data retrieved from NASA's CERES instruments, located onboard several Earth observation satellites [12]. In this way, the method takes into account real environmental data. The CERES website provides scientists with a wide range of measured data with different spatial and temporal resolutions. The two variables used for this study are the so-called 'all sky top of the atmosphere albedo' (TOA albedo) and 'all-sky TOA longwave flux'.

All sky TOA albedo is the ratio between the broadband (0.2–5 μm) shortwave reflected flux and the incoming solar flux at the top of the atmosphere. On the other hand, all-sky TOA longwave flux is the CERES-observed broadband emitted thermal outgoing longwave flux at the top of the atmosphere. The all-sky condition includes the effect of