Thermal design and preliminary performance evaluation of the cooling system for BaR-SPOrt

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BaR-SPOrt **(Balloon-borne Radiometer for Sky Polarisation Observations) is a project to measure the linearly polarised emission of 20° x 20° sky patches at 32 GHz and 90 GHz from a stratospheric balloon. The instrument shares most of the SPOrt-ISS know-how. It consists of correlation polarimeters for direct measurements of the Q and U Stokes parameters, coupled to an optical system providing a beam of 0.5 deg (32 GHz) and 0.2 deg (90 GHz). Its aim is the study of the polarisation of the diffused Galactic Background as well as the Cosmic Microwave Background Radiation (CMBR).**

The instrument thermal design and the preliminary performance evaluation of the active cooling system are described.

THERMAL DESIGN

To maximize the sensitivity of a radio receiver, it is necessary to minimize the noise injected by its front-end. In the case of a polarimeter such as the BaR-SPOrt, this means to cool at cryogenic temperatures both the system Polariser - OMT (Orthomode transducer) and the first stage of the low noise amplifiers (HEMT). To reach and keep constant such a temperature a cryostat, housing in a vacuum chamber the cold components, and a proper cooler are necessary.

Drifts and instability of the temperature of the warm and cold parts generate thermal noise (offset and its fluctuations), which means degradation of the instrument sensitivity. In order to control and remove efficiently such offset fluctuations and to guarantee the goal sensitivity, the thermal instability inside the cryostat has to be lower than 0.1 K. This is the reason why it has been adopted a shield, which temperature is actively controlled, in order to stabilize the inner thermal environment both for the warm parts and the cold box which "radiatively sees" such a shield and a closed loop cryocooler (CLC) with a cold finger characterized by a high temperature stability (0.1 K).

The polarimeter design

The mechanical, thermal and electromagnetic design of the Bar-SPOrt polarimeter has been developed to minimize instrumental effects and to increase long term stability in order to reduce 1/f noise effects.

The main instrumental characteristics are:

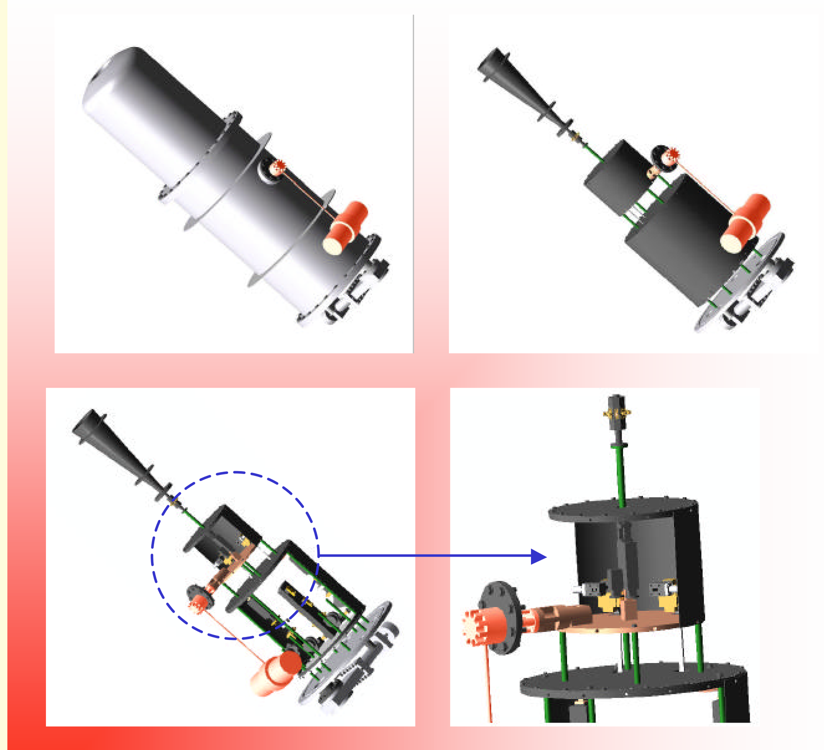
- a) low cross-polarisation optics providing HPBW of 0.5 and 0.2 deg (32 and 90 GHz)
- b) a cryostat to cool (T < 80.0 ± 0.1 K) LNAs, circolators, polariser and OMT (see Figg. 1, 2, 3, 4) by a closed loop cryocooler. The horn might be cooled as well. A thermal shield, temperature regulated (T ~ 300.0 ± 0.1 K), located inside the cryostat, is foreseen to increase the thermal stability
- c) custom design internal calibrator for polarised reference signals
- d) custom design waveguide Hybrid Phase Discriminator device, inserted in the correlation unit, with a rejection to unpolarised component equal to 30 dB
- e) custom design OMT with high isolation between channels (> 60 dB) to limit the unpolarised component contamination

Thermal Specifications

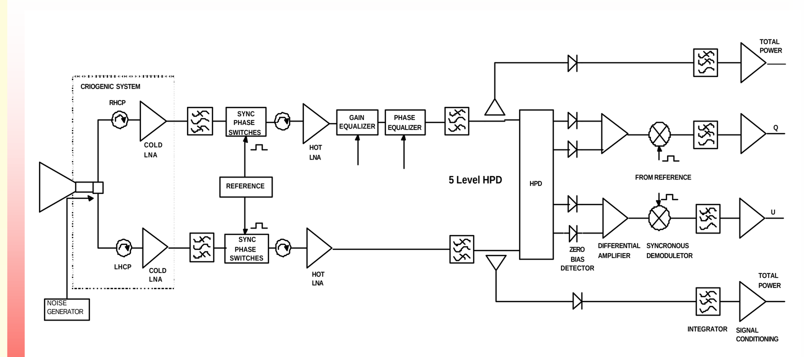
COLD environment (Maximum Temperature)	WARM environment (Maximum Temperature)
80.0 ± 0.1 K	300.0 ± 0.1 K

BaR SPOrt Characteristics

FREQUENCY	BANDWIDTH	ANGULAR RESOLUTION	INSTANTANEOUS SENSITIVITY	LIFETIME
32 GHz	10 %	0.5 deg	0.5 mK $s^{-1/2}$	~ 2 weeks
90 GHz	10 %	0.2 deg	0.7 mK $s^{-1/2}$	~ 2 weeks



3 - D Vision of the cryostat



The schematic diagram of the correlation polarimeter.
The cold box is highlighted.

THERMAL BUDGET

In order to cool a box at a fixed temperature T by a CLC, we must guarantee that the thermal input on its cold finger is not greater than the refrigeration power of the mechanical cryogenerator at such temperature T.
It is possible to estimate the thermal input on the cryocooler according to the following budget:

$$\dot{Q} = \dot{Q}_R + \dot{Q}_C + \dot{Q}_J$$

where the total thermal input equals the radiative (R) and the conductive (C) heat plus the heat dissipated by Joule effect (J) in the active components. The convective exchange is negligible because the pressure level in the vacuum chamber will be 10^{-5} – 10^{-6} mbar.

The radiative thermal input is due to the emission of the inner surface of the cryostat "seen" from the cold box and the emission of the cold box surface itself.

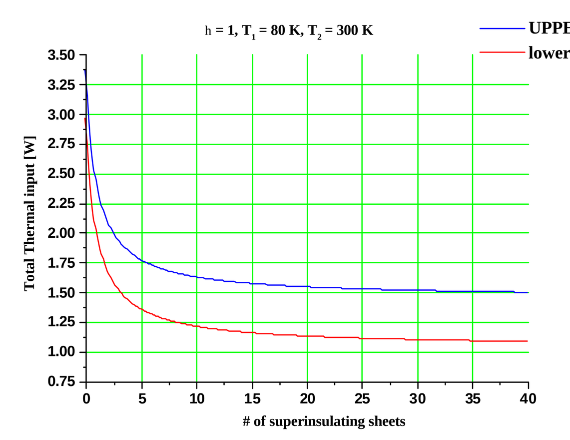
The conductive thermal input is due to the waveguide (WG) (fiberglass with internal silver coating) between the feed (300 K) and the polariser (80 K), the two WG (stainless steel with internal silver coating) from the first stage of cold the HEMT to the warm box, the four spacer (fiberglass) between the cold and the warm box and the cryogenics wires for the LNAs power supply.

In order to understand how the total heat could vary, modifying some technical parameters, we explore two possibilities to maximize (UPPER case) and minimize (lower case) the total thermal input on the cold finger. We consider the following designs:

UPPER case:
1) the two WG (L_A = 0.681 cm, L_B = 0.325 cm, t = 0.02 cm, l = 10 cm) from the HEMT to the warm box are internal silver coated (5 mm)
2) the four spacer are full (F = 1 cm, l = 8 cm)
3) the lenght of the cryogenics wires (# = 38, 9 each HEMT and 2 each thermometer (10)) is four times longer than in the min case

lower case:
1) the two WG from the HEMT to the warm box are not internal silver coated
2) the four spacer are hollow with a fixed thickness (t = 3 mm)
3) the lenght of the cryogenics wires is l = 10 cm

In both cases, assuming the maximum efficiency of the heat transfer (h = 1) due to Joule effect and using superinsulation techniques to reduce the total thermal input, the *total heat insisting on the cold finger vs the number of the superinsulating sheets* is shown in the plot below.

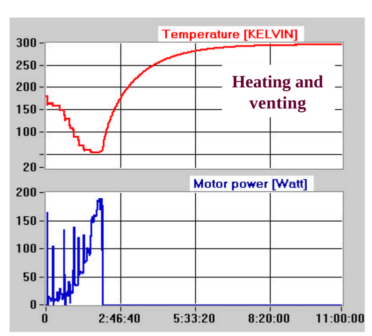


Considering the UPPER case and the specifications of the Stirling CLC (6,4W @ 80 K, 180 W Power drawn) provided by the manufacturer (see section below), the goal of 80 K will be achievable.

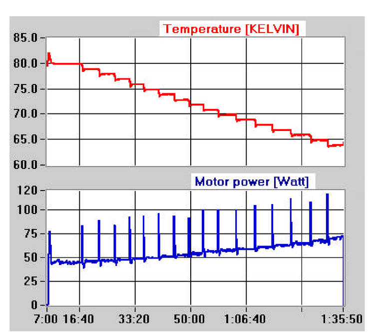
PRELIMINARY EVALUATION OF THE ACTIVE COOLING SYSTEM

First measurements related to the cryocooler have been made in order to verify both its power refrigeration (Stand Alone Test) and its temperature stability. During these measurements (two runs), a P_{MAX} (maximum motor power) of 180 W has been set and 1 W has been applied by the heater directly linked to the cold finger.

In this test run the cold finger temperature has been lowered up to 55 K by 1 K steps in order to determine the minimum temperature the cryocooler is able to keep constant with an heat input of about ~3 W (see later).
It is possible to see that the temperature stability, connected to the one of the power consumption, is reached when the latter is lower than P_{MAX}.
In fact, since a sudden decreasing of the cold finger temperature implies a sudden spike of motor power absorption, such a spike has to be lower than P_{MAX} in order to don't produce an overcurrent. A long time duration of such a current (some seconds), will imply a switching off of the cryocooler (failure ® safe mode).
The lowest stable temperature reached (first run) is 55.0 ± 0.1 K.
Lower temperatures imply a power consumption exceeding the set limit (180 W).

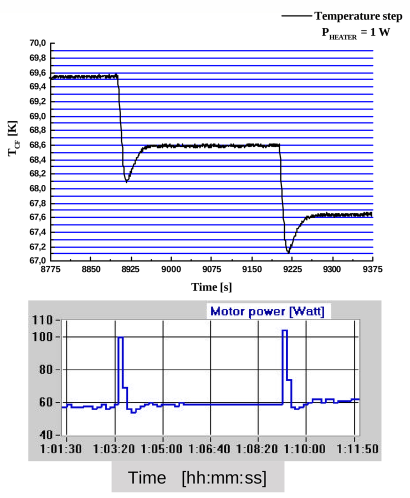


First run

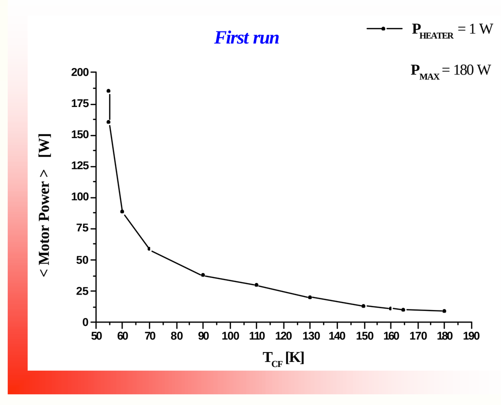


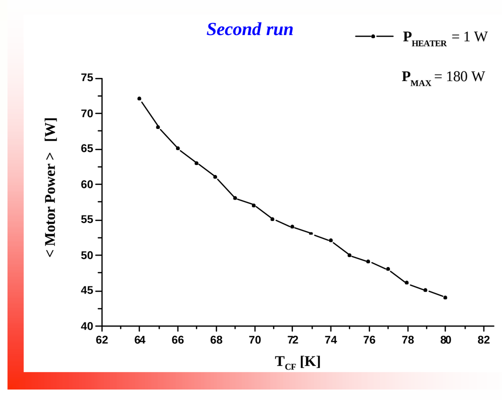
Second run

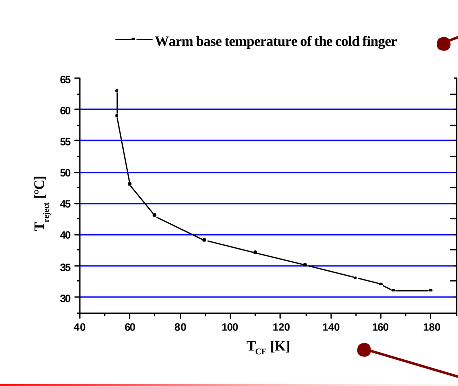
From the control panel to the analysis of the experimental data….

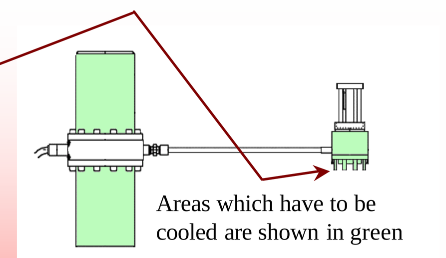


Stability better than 0.1 K.
During these measurements the cryocooler has fitted the thermal stability specifications!

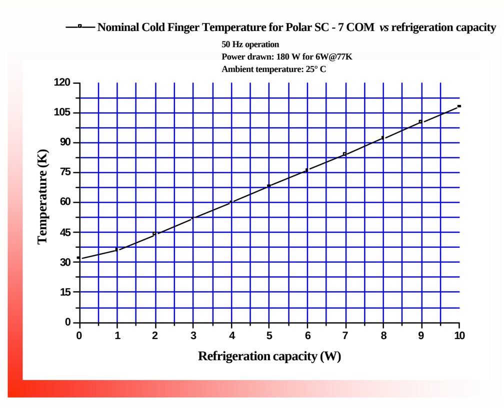








… to the extrapolation from the data provided by the manufacturer!



With respect to the minimum stable temperature (55.0 ± 0.1K) of the cold finger, from the plot on the left it is possible to extrapolate a cooling power of about 3.2 W. At 80 K such a cooling capacity requires a power consumption of ~ 45W. Considering the "UPPER case" of the thermal budget (~ 1.75W for 10 layers of MLI) and the thermal specifications as exposed in the upper panel, the performance of the cryocooler adopted in term of low temperature and stability meets the thermal requirements for an active cooling system of the BaR-SPOrt polarimeter.
Since by means of the heater 1W has been applied on the cold finger, we can estimate, from the manufacturer specificatation of the cooler, a background heat input of the test vacuum chamber of ~2.2 W.

WEB SITES
http://sport.tesre.bo.cnr.it
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