BaR-SPOrt: a technical overview

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Abstract. BaR-SPOrt is a project to measure the linearly polarised emission of 20°x20° sky patches from a stratospheric balloon, at 32 GHz and 90 GHz. It consists of correlation polarimeters for direct measurements of the Q and U Stokes parameters, coupled to an optics providing a beam of 0°.5 (32 GHz) and 0°.2 (90 GHz). The instrument design is described. Particular emphasis is put on the hardware solutions adopted to reduce the systematic effects in high sensitivity polarisation measurements.

INTRODUCTION

BaR-SPOrt (Balloon-borne Radiometer for Sky Polarisation Observations) is a balloon experiment housing correlation microwave polarimeters (32 & 90 GHz) for the direct measurement of the Q and U Stokes parameters with HPBW=0°.5 & 0°.2. It shares most of the SPOrt know-how [1, 2], aimed at studying the polarisation of the Cosmic Microwave Background (CMB) as well as the diffused Galactic Background. The polarised component of the CMB can be related to cosmological parameters, providing information about the nature of the primordial fluctuations and the re-ionization era, thereby allowing to discriminate among different cosmological models. The study of the linearly polarised emission is fundamental to understand the physical processes taking place in our Galaxy [3]. The Galactic emission represents also a foreground signal to be carefully removed from the measurements of CMB experiments. BaR-SPOrt is an ASI (Italian Space Agency) funded experiment which should be ready to fly by the end of 2003. The first launch, which might be from Antarctica, will carry only the 32 GHz channel. The 90 GHz will be implemented as a second step. BaR-SPOrt scientific goals are the building of linear polarisation maps of sky patches and the tentative detection of the linearly polarised component of the CMB radiation, which is expected to be at μK level. The main features of the BaR-SPOrt experiment are summarized in Table 1.

TABLE 1. BaR-SPOrt main characteristics: σ_{1s} is the instantaneous sensitivity, σ_{PX} and σ_{FP} are the final per pixel and the full patch rms sensitivities for a flight of two weeks.

Frequencies (GHz)	Bandwidth	Beam	σ_{1s}[mKs$^{1/2}$]	σ_{PX}[μK]	σ_{FP}[μK]
32	10%	0.5°	0.5	18	0.4
90	10%	0.2°	0.7	64	0.6

BAR-SPORT INSTRUMENT DESIGN

A brief overview

The detection of a signal as low as that expected from CMB polarisation ($\leq 1\ \mu$K) asks for extremely sensitive and stable radiometers. The BaR-SPOrt instrument design has been developed to minimize instrumental effects and to reduce 1/f noise, thereby increasing the long term instrument stability. Particular care has been taken in the realisation of the antenna system to control the spurious polarisation [4]. Correlation techniques are widely adopted in high sensitivity measurements because of their capability to reduce the effects of gain fluctuations. Residual instabilities are usually recovered by using destriping tecniques [5, 6, 7, 8], which require the radiometer to be stable over a single scan period ($30 \div 60$ s for BaR-SPOrt). Starting from the correlation radiometer sensitivity equation:

$$\Delta T_{rms} = \sqrt{\frac{k^2 T_{sys}^2}{B\tau} + T_{offset}^2 \left(\frac{\Delta G}{G}\right)^2 + \Delta T_{offset}^2} \tag{1}$$

care has been taken to reduce the system noise temperature (T_{sys}), the gain fluctuations ($\Delta G/G$), the instrumental offsets (T_{offset}) and the offset fluctuations (ΔT_{offset}), by means of correlation and modulation techniques.
The main instrumental characteristics are (see also Table 1):

- direct amplification architecture: no down conversion to avoid possible phase error;
- low cross-polarisation optics providing HPBW of $0^\circ.5$ ($0^\circ.2$) at 32 GHz (90 GHz);
- correlation unit based on a custom design waveguide Hybrid Phase Discriminator (HPD), with unpolarised component rejection equal to 30 dB [9];
- custom design Orthomode Transducer (OMT) with high isolation between channels ($>$ 60 dB) to limit contaminations from the unpolarised component [4, 9];
- phase modulation (lock-in system) and correlation providing $>$ 70 dB of total rejection to the unpolarised component;
- a cryostat (see Figure 1) to cool ($T < 80.0 \pm 0.1$ K) LNAs, circulators, the polariser and the OMT by a closed loop cryocooler. The horn, at present designed to be at 300 K, might be cooled as well. A thermal shield, stabilised at temperature $T \cong 300.0 \pm 0.1$ K, is foreseen to increase the thermal stability;
- custom design internal calibrator to inject reference polarised signals.

Considering the parameters of the antenna system shown in Table 2, the physical temperatures of its devices and the noise temperature of the HEMT (30 K), the expected system temperature for the 32 GHz channel is: $T_{sys} \simeq 40K$.

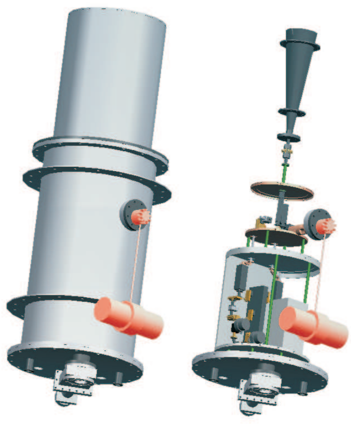


FIGURE 1. The outer and inner parts of the cryostat.

TABLE 2. Goal attenuation parameters of the 32 GHz antenna system.

Feed horn [dB]	Polariser [dB]	OMT [dB]
0.05	0.1	0.1

The polarimeter

The most peculiar features of the BaR-SPOrt polarimeter are: the direct and simultaneous measurement of Q and U, by correlating the two circularly polarised components of the radiation; the adoption of cryogenic Low Noise Amplifiers (LNA); the implementation of a *new concept* waveguide device (HPD) for on board analog correlation. The electric scheme of the BaR-SPOrt radiometer is shown in Figure 2. The choice of correlating the circular components is due to the expression of the Stokes parameters with respect to the basis on which the electric field is decomposed [3]:

$$\begin{aligned} I &\propto \langle|\vec{E}_x|^2\rangle + \langle|\vec{E}_y|^2\rangle & \qquad I &\propto \langle|\vec{E}_L|^2\rangle + \langle|\vec{E}_R|^2\rangle \\ Q &\propto \langle|\vec{E}_x|^2\rangle - \langle|\vec{E}_y|^2\rangle & \qquad Q &\propto \langle|\vec{E}_L||\vec{E}_R|\cos(\delta_c)\rangle \\ U &\propto \langle|\vec{E}_x||\vec{E}_y|\cos(\delta)\rangle & \qquad U &\propto \langle|\vec{E}_L||\vec{E}_R|\sin(\delta_c)\rangle \\ V &\propto \langle|\vec{E}_x||\vec{E}_y|\sin(\delta)\rangle & \qquad V &\propto \langle|\vec{E}_L|^2\rangle - \langle|\vec{E}_R|^2\rangle \end{aligned} \tag{2}$$

where I describes the total power, Q and U the linear polarisation, V the circular polarisation, $\vec{E}_x$, $\vec{E}_y$ and $\vec{E}_L$, $\vec{E}_R$ are the linearly and circularly polarised components of the electric field, respectively, and δ and δ_c are the phase differences of the two linear and circular components, respectively. Thus, simultaneous Q and U outputs cannot be obtained by correlating the linear components. Figure 2 shows how a phase delay of 90° between the linear components, inserted by the polariser, and a rotation of 45° between the reference frame of the OMT and the polariser can transform the linear components into circular ones, then fed to the HPD.

The use of cryogenic LNAs is necessary to reduce the system noise temperature. The BaR-SPOrt radiometers have two LNA amplification stages: the first one is cryogenic ($\sim$ 80K) and the second one is warm ($\sim$ 300K). A mechanical

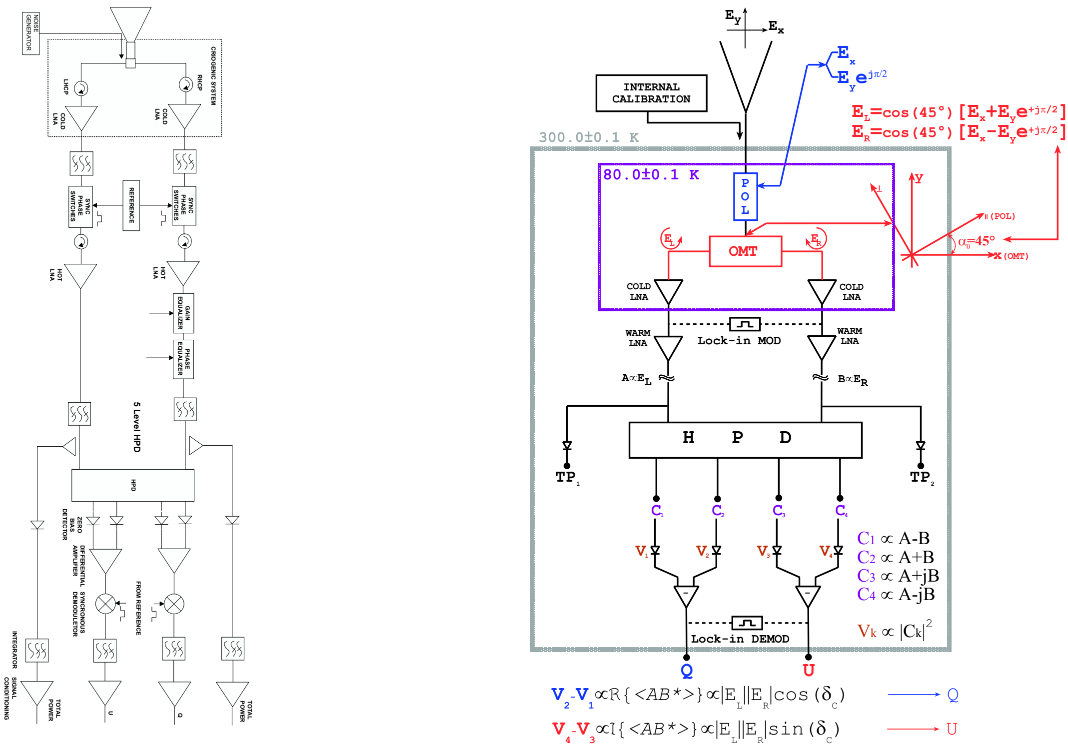


FIGURE 2. Electric scheme (left) and operational scheme (right) of BaR-SPOrt polarimeters.

Stirling cryocooler with closed loop control will provide the cooling down to 80 K with stability of 0.1 K. Since the BaR-SPOrt performances strongly depend on the temperature stability, particular care has been put in the thermal design. As already mentioned, an active temperature control is planned also for the warm parts.
The correlation unit is based on the HPD [1], a passive microwave circuit that processes the signal in order to have four outputs proportional to:

$$\vec{E}_R - \vec{E}_L \qquad \vec{E}_R + \vec{E}_L \qquad \vec{E}_R + j\vec{E}_L \qquad \vec{E}_R - j\vec{E}_L \tag{3}$$

After square law detection the four HPD outputs become (Figure 2):

$$\begin{aligned} V_1 &\propto [|\vec{E}_L|^2 + |\vec{E}_R|^2 - 2\Re(\vec{E}_L \cdot \vec{E}_R{}^*)] \\ V_2 &\propto [|\vec{E}_L|^2 + |\vec{E}_R|^2 + 2\Re(\vec{E}_L \cdot \vec{E}_R{}^*)] \\ V_3 &\propto [|\vec{E}_L|^2 + |\vec{E}_R|^2 + 2\Im(\vec{E}_L \cdot \vec{E}_R{}^*)] \\ V_4 &\propto [|\vec{E}_L|^2 + |\vec{E}_R|^2 - 2\Im(\vec{E}_L \cdot \vec{E}_R{}^*)] \end{aligned} \tag{4}$$

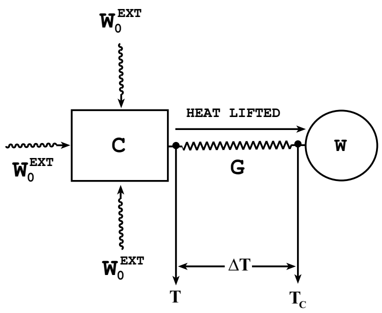
which are properly differentiated to get as final outputs the two quantities:

$$\begin{aligned} V_2 - V_1 &\propto |\vec{E}_L||\vec{E}_R|\cos(\delta_c) \longrightarrow Q \\ V_4 - V_3 &\propto |\vec{E}_L||\vec{E}_R|\sin(\delta_c) \longrightarrow U \end{aligned} \tag{5}$$

After integration, these provide time averaged values proportional to the Q and U Stokes parameters. One of the most important HPD specifications is the rejection of the unpolarised component of the signal, mainly due to the CMB and to the system noise temperature.

Thermal analysis and vacuum window

The request for high precision and stability instruments, necessary to measure faint polarisations, translates also in an *ad hoc* thermal design. Models are currently being developed to understand the effects of the thermal instability caused by the closed loop cryocooler (CLC) as well as the spurious polarisation induced by the dielectric vacuum window (usually polymers, see Figure 3). The CLC is a thermo-mechanical device which cools the components to low temperature. Its cold finger is linked to the cold box by a copper rod. The study is related to the thermal noise caused by the fluctuations of the cryocooler refrigeration power, which in turn induce Cold Finger Temperature Fluctuations (CFTF). The maximum allowed thermal fluctuations, over one scanning period, is 100 mK. Since CFTF induce fluctuations to the temperature working point, the study of this thermal noise is very important for the definition of the instrument thermal specifications. The model provides the power spectrum of the temperature fluctuations of



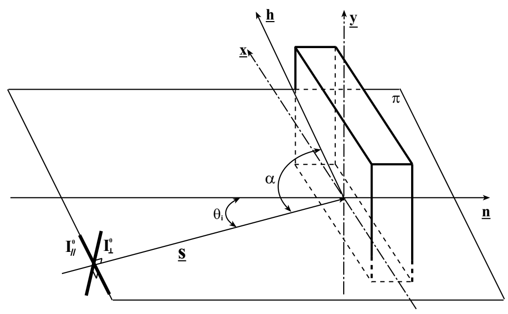


FIGURE 3. The cryocooler thermal analysis (left): C represents the thermal capacity of the warm component (WC), G the conductance between the cryocooler (W) and WC, T and T_C the temperature of WC and W, respectively, ΔT the temperature gap, W_0^{EXT} the thermal input EXTernal to the C-G-W sub-systems. The vacuum window analysis (right): $\underline{h}$ represents the alignment direction of the structural units inside the sheet, $\underline{n}$ is the normal to the sheet, $\underline{S}$ the incidence direction, π the incidence plane defi ned by $\underline{n}$ and $\underline{h}$, $I_{\parallel}^0$ e $I_{\perp}^0$ the intensities related to the parallel and normal vibration modes with respect to the π plane, θ_i is the incidence angle, $\underline{x}$ and $\underline{y}$ the components individuating the laboratory reference frame and α the angle between $\underline{h}$ and $\underline{S}$.

the device which has to be cooled. The power spectrum $P_T^{WC}(f)$ depends on the details of the CLC, the conductance G

between the cryocooler and the Warm Component (WC), and the thermal capacity C of the WC (see 6 and [10, 11]):

$$P_T^{WC}(f) \quad = \quad (1+\frac{\alpha}{G})^2 \frac{P_T^{CF}(f)}{1+(\frac{f}{f_C})^2} \tag{6}$$

where $P_T^{CF}(f)$ is the power spectrum of the cold finger temperature, $f_C = \frac{G}{2\pi C}$ is the cut–off frequency and α is the slope of the cryocooler calibration curve $W = \alpha T_C + \beta$ (in the temperature working range, the trend of the refrigeration power W is linear in T_C). The consistency of this model will be tested in the laboratory.

The manufacturing of the dielectric material making the vacuum window creates, inside it, chains of polymers aligned along some directions (see Figure 3). Those chains induce birefringence ($\Re\{n_{\parallel} - n_{\perp}\} \neq 0$ where $\parallel$ and $\perp$ individuate the principal directions with respect to the π plane) and dichroism ($\Im\{n_{\parallel} - n_{\perp}\} \neq 0$), as in uniaxial crystals (see [12, 13, 14, 15, 16, 17, 18, 19]), though their origin is quite different, being linked to the manufacturing and not intrinsic. The optical anisotropy then induces spurious polarisation and signal depolarisation, superimposed to the usual trend of isotropic dielectrics (analysis performed by Fresnel's coefficients). In particular, also in the best case of isotropic diffuse radiation, a residual (spurious polarisation) is produced when integrating the signal over the antenna pattern, because of the breaking of the azimuthal symmetry originating from the polymer chain alignment. On the contrary, the same integration should provide a null spurious signal, in case of isotropic dielectrics which have azimuthal symmetry. The model and the measurements should verify the different trends between isotropic and anisotropic dielectric.

In conclusion, the BaR-SPOrt instrument represents an opportunity to test *state of the art* technological solutions that are the base also for more ambitious CMBP space–projects [1, 2, 4]. Moreover, by improving technologies for high sensitivity polarisation measurements at microwaves and millimetric wavelengths, it will play an important role to promote instrumental developments useful for ground applications (radioastronomy).

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