SPOrt: a Microwave Experiment for CMB Polarized Emission Measurement Designed to Minimize Instrumental Polarization.

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Abstract — **The polarization of the Cosmic Microwave Background is one of the most powerful tools for cosmological investigations. In spite of its importance, it is very faint and can be as low as 10^{-7} of the total signal. In general, state of the art microwave passive devices do not match the requirements for a clean detection of this signal. Thus, a significant effort has to be spent analyzing the system, identifying critical components and developing new devices with higher performances. This paper presents the case of the SPOrt experiment, where the system has been carefully analyzed and most of the passive devices have been developed with the aim of keeping systematics lower than the signal to be detected.**

1 Introduction

The Cosmic Microwave Background Polarization (CMBP) is a powerful tool complementary to the CMB Anisotropy (CMBA) to undestand the origin and evolution of the Universe [1, 2].

The precise information provided by CMBA experiments (WMAP [3], with a breathless spectrum measurement, several ground experiments (See Ref. [4, 5, 6] among the others) and the forthcoming PLANCK mission) will be completed by a full characterization of the CMBP emission [2]. In particular, it will provide a direct measurement of cosmological parameters that CMBA alone is not able to determine [2, 7, 8]. On large angular scales it will allow the determination of the optical depth τ in the dark ages and the epoch $z_{\rm ri}$ at which the re-ionization occurred providing us the formation epoch of the first structures and the re-ionization history. In addition, the E-mode of CMBP brings important information also at subdegree angular scales. Inflation predicts *coherent* primordial fluctuations which leave a well defined signature: a Doppler peak pattern with maxima in the T spectrum corresponding to minima in the E one and viceversa. Thus, a precise measurement of the E-mode power spectrum at subdegree scales leads to an indirect check of the inflationary model [9].

The detection of the B-mode is even more exciting, although the signal is very weak. It is generated by the tensor gravitational wave background produced at the inflation era and its level is directly related to the tensor-to-scalar perturbation ratio T/S, whose value is in turn related to the energy of the Universe at the inflation time [7, 8]. Thus, the measurement of the B-mode represents a clean estimate of the energy at which the inflation occurred and a way to disentangle among the several existing models.

In spite of its importance, the CMBP predicted level for the E-mode is very low (few μK on subdegree scales and less than 1 μK on large scales), less than 10% of the already faint emission of CMBA. After a sequence of lower and lower upper limits, the first detection has been recently claimed by the DASI team on subdegree scales [10], while the WMAP experiment has provided a clear evidence of its existence measuring the cross spectrum C^{TE} between CMBA and CMBP on both small and large angular scales. The latter is particularly important, because it has led to the first measurement of τ at an unexpected high value ($\tau = 0.17 \pm 0.04$) [11], pushing toward z = 15-20 the first structure formation in the Universe. On the other hand, the WMAP team found high systematic error contamination at level of the CMBP signal itself, the experiment being not designed for faint polarization observations. Besides the cross-spectrum C^{TE}, they were not able to provide a pure CMBP measurement (E-mode spectrum C^E) in its first-year data release and their intention is to reach a better understanding on possible systematics contaminations before to make available data concerning the E-mode.

A clean measurement of the weak CMBP signal, thus, requires expressly devoted instruments, in or-

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der to keep systematic effects under control at level needed by CMBP itself. This is particularly true in the light of next generation experiments aimed at the B-mode detection, whose signal is faint not only with respect to the CMBA (the B-mode is expected to be at 0.1 μK level, about 3 orders of magnitude lower than CMBA and 7 orders lower than the uniform $3K$ background), but also with respect to the other CMBP component (E-mode).

CMB observations are mostly performed in the microwave/millimeter range (around 100 GHz) where other astrophysics sources are at minimum (see Ref. [12] and references therein). In particular, the most important contaminat is expected to be the Galaxy with its diffuse synchrotron emission. However, also this source is practically unknown in the microwave range, its emission being measured only at low frequency (less than 2.7 GHz) and with a very partial sky coverage.

The design of a clean instrument requires a careful analysis of possible contamination from each individual component, in order to identify both the critical devices and the parameters to keep under control. Here we present the case of SPOrt, an experiment devoted to CMBP measurements on large scales where the systematic effects are more important.

2 The SPOrt Experiment

The Sky Polarization Observatory (SPOrt)[1] experiment is aimed at developing an instrument devoted to CMBP measurements and filling the current gap in measurements of the diffuse polarized emission in the 22-90 GHz range on large angular scales ($\theta > 7°$).

SPOrt is an experiment funded by the Italian Space Agency (ASI) and it has been selected by ESA to be flown onboard the International Space Station (ISS) for a minimum lifetime of 18 months in the Early Utilization Phase. Together with BaR-SPOrt [13] and related observational and technological activities, it is part of the SPOrt Programme [14] aimed at CMBP investigations.

SPOrt is the first space instrument devoted to measuring Q & U Stokes parameters in the microwave domain. Its main aim is to explore the polarized sky in the 22-90 GHz range with an instrument whose residual systematics are lower than the expected faint E-mode on large angular scales. This can be done only by all-sky surveys accessible only from space (SPOrt will cover about 80% of the sky) and by instruments designed to be as much as possible insensitive to instrumental polarization.

[1]`http://sport.bo.iasf.cnr.it`

An example of the results achievable by SPOrt on the E-mode spectrum is shown in Figure 1, while Table 1 reports the main characteristics of the experiment.

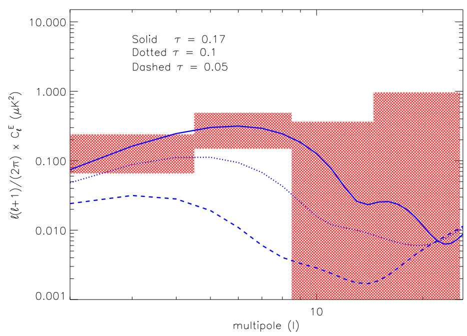

Figure 1: Errors (68% C.L.) on the power spectrum C_ℓ^E achievable by SPOrt in the case of $\tau = 0.17$.

ν [GHz]	BW	$\Delta\theta$ [°]	σ_{1s} [mKs$^{1/2}$]	σ_{PX} [μK]
22	10%	7	0.5	1.6
32	10%	7	0.5	1.6
90	10%	7	0.57	1.8

Table 1: SPOrt main characteristics: BW is the bandwidth, $\Delta\theta$ the FWHM, σ_{1s} the istantaneous sensitivity (1 second) and σ_{PX} the final sensitivity per pixel. 90 GHz values are for two receivers.

Great care has been taken to optimize the instrument design with respect to systematics generation, long term stability and observing time efficiency.

The following major choices were adopted for the SPOrt design:

1. correlation polarimeters to improve the stability;
2. correlation of the two circularly polarized components E_L and E_R to directly and simultaneously measure both Q and U (100% observing time efficiency). This optimizes the sensitivity with respect to other schemes like correlation or difference of linear polarized components, which provide either Q or U at once;
3. detailed analysis of the radiometer scheme to identify *critical* components and the specifications they have to satisfy;
4. custom development of most critical components when the existing state-of-the-art is not enough.

3 Design Analysis

Our analysis begins with the radiometer equation [15] which allows us to identify the relevant parameters to be controlled for minimizing systematic effects. In fact, in the expression[2]

$$\Delta T_{\rm rms} = \sqrt{\frac{k^2\, T_{\rm sys}^2}{\Delta\nu\,\tau} + T_{\rm off}^2 \left(\frac{\Delta G}{G}\right)^2 + \Delta T_{\rm off}^2} \quad (1)$$

the first term represents the white noise of an ideal and stable radiometer, while the others represents the additional noise generated by instrumental instabilities, namely the gain and offset fluctuations (second and third terms, respectively). The ideal behaviour is preserved provided that the offset is kept under control.

Correlation receivers are intrinsically more stable because of their lower offset generation. SPOrt adopts a scheme correlating the two circular polarized components collected by a dual-polarization feed horn and extracted by a polarizer and an Orthomode Transducer (OMT). After amplification, the two components are correlated by the correlation unit (CU) consisting in a Hybrid Phase Discriminator (HPD), diodes and differential amplifiers, whose outputs are the two Stokes parameters Q & U.

In order to minimize the offset level an analysis has been carried out to identify the devices generating offset and the parameters to be controlled. The analysis shows the offset is generated in both the CU and the antenna system (horn, polarizer and OMT).

The CU provides a negligible contribution thanks to a customly developed HPD optimized to have a high rejection of the unpolarized component (> 30 dB [16]). A lock-in system improves the total rejection to 60 dB, making the offset not significant. The CU performances have been already tested with the receiver of the BaR-SPOrt experiment.

Consequently, the antenna system remains the only source of significant offset. Carretti et al. [17] found that OMT and polarizer generate the leading contributions ruled by:[3]

$$\begin{aligned} T_{\rm offset} &= SP_{\rm OMT}\left(T_{\rm sky} + T_{\rm noise}^{\rm Ant}\right) \\ &+ SP_{\rm pol}\left(T_{\rm sky} + T_{\rm noise}^{\rm horn} - T_{\rm ph}^{\rm pol}/\eta\right), \quad (2) \end{aligned}$$

where the two quantities

$$SP_{\rm OMT} = 2\,\frac{\Re(S_{A1}S_{B1}^*)}{|S_{A1}|^2}, \quad (3)$$

$$SP_{\rm pol} = \frac{1}{2}\left(1 - |S_\perp|^2 / |S_\parallel|^2\right), \quad (4)$$

describe the offset generation of OMT and polarizer, respectively. Uncorrelated signals (noise and sky) are partially correlated because of the OMT cross–talk (S_{A1} and S_{B1} are the transmission and cross-talk coefficient of the OMT, respectively) and of the polarizer attenuation difference ($S_\parallel$ and $S_\perp$ are the attenuations of the two polarizations in the polarizer).

Equation (1) allows the identification of instability sources, but their effects are better quantified in terms of the knee frequency ($f_{\rm knee}$), that provides the time scale at which the $1/f$ component of the noise power spectrum prevails on the white noise. Destriping techniques can remove most of the effects of the $1/f$ noise, in the case of $f_{\rm knee}$ lower than the signal modulation frequency [18]. For SPOrt this corresponds to the orbit frequency $f_{\rm orbit} = 1.8 \times 10^{-4}$ Hz.

The knee frequency of a correlation receiver is related to that of its amplifiers ($f_{\rm knee}^{\rm lna}$) by the formula

$$f_{\rm knee} = \left(\frac{T_{\rm off}}{T_{\rm sys}}\right)^2 f_{\rm knee}^{\rm lna} \quad (5)$$

Current InP technology provides W-band low noise amplifiers with $f_{\rm knee}^{\rm lna}$ = 100–1000 Hz, making mandatory the adoption of correlation receivers.

From equations (2)-(4) the SPOrt needs for the OMT cross-talk and the difference between the attenuations of the polarizer have been quantified in -60 dB and -30 dB, respectively. Actually, these lead to an offset value as low as $T_{\rm offset} \sim 50$ mK that, combined with a $T_{\rm sys} \sim 100$ K, gives the knee frequency

$$f_{\rm knee} \sim 2.5 \times 10^{-7} f_{\rm knee}^{\rm lna} \quad (6)$$

matching the condition for a successful destriping ($f_{\rm knee} < f_{\rm orbit}$).

However, state-of-the-art OMTs do not satisfy these specifications, and, as for the HPD, a custom hardware development has been required to the SPOrt team. Figure 2 shows the result obtained for the 32 GHz channel: a cross-talk as low as -65 dB

[2] $T_{\rm sys}$, $T_{\rm off}$ and $\Delta T_{\rm off}$ are the system temperature, the offset equivalent temperature and its fluctuation, respectively; G is the radiometer gain, τ the integration time, $\Delta\nu$ the radiofrequency bandwidth and k a constant depending on the radiometer type.

[3] $T_{\rm sky}$ is the signal collected from the sky, $T_{\rm noise}^{\rm horn}$ is the noise generated by the horn alone, $T_{\rm noise}^{\rm Ant}$ is the noise temperature by the whole antenna system, η is the efficiency of the feed horn and $T_{\rm ph}^{\rm pol}$ is the physical temperature of the polarizer.

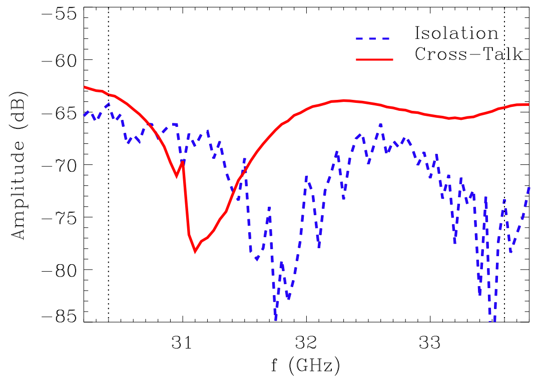

Figure 2: Isolation between the two rectangular ports and cross-talk between the two polarizations for the 32 GHz SPOrt OMT.

has been achieved, comfortably below the -60 dB goal.

Besides the offset generation, the SPOrt team has identified another source of systematics: the spurious polarization generated by the optics [17]. This is due to the anisotropy distribution of the unpolarized radiation modulated by the f pattern (combination of co- and cross-polar patterns of the feed):

$$T^{\rm horn} = \int \Theta\, f\, d\Omega, \qquad (7)$$

where the integration is performed on the first quadrant and Θ is a combination of the anisotropy field coming from all of the four quadrants (see Ref. [17] about details of Θ and f expressions). In the case of SPOrt feed horns, the contamination is found to be $T^{\rm horn} < 0.2\ \mu$K. Due to its intrinsic asimmetry, off-axis optics with the same cross-polar pattern level would imply a spurious contribution 8-10 dB higher.

In summary, the faint CMBP signal requires dedicated instruments and the SPOrt team has spent (and is still spending) a big effort in realizing the best correlation radiometer architecture for polarization observations. It represents also an important technological development toward B-mode measurements, that represent the real challenge for next generation space experiments.

Acknowledgments

We thank the whole SPOrt collaboration and V. Natale for useful discussions. We acknowledge use of CMBFAST package. SPOrt is an ASI funded project. We thank also ESA for providing the flight opportunity onboard the International Space Station.

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