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The SPOrt Project: an Experimental Overview

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Abstract. The Sky Polarization Observatory (SPOrt) is presented as a project aimed to measure the diffuse sky polarized emission, from the International Space Station, in the frequency range 20–90 GHz with 7° of $HPBW$. The SPOrt experimental configuration is described with emphasis on the aspects that make SPOrt the first European scientific payload operating at microwave wavelengths.

INTRODUCTION

The first idea of the SPOrt project was born in 1996 in reply to the ESA Call for Ideas for the Early Utilization Phase of the International Space Station (ISS)(1). At that time SPOrt was aimed to measure only the polarization of the Galactic Background in the frequency range 10–30 GHz, in order to fill the gap in observational data in a region of particular interest for Cosmic Background Radiation (CBR) measurements. For many reasons (see for example Cortiglioni et al. (2) and Fabbri et al. (3)) the current SPOrt configuration is quite different from the original one, including among its objectives also the attempt to measure CBR linear polarization. This more ambitious scientific goal can be reached only with an improved design, which is characterized by:

- 20–90 GHz frequency coverage, in order to optimize foreground subtraction;
- the same beamwidth for all channels ($HPBW = 7°$): no normalization is needed in data analysis;
- Phase Switched Correlation Radio-Polarimeters (PSCRP) with direct amplification chains, which provide simultaneously Q and U Stokes parameters almost free from offsets, drifts and $1/f$ noise;
- very simple optical design without any reflector optics in order to have rejection to unpolarized components as high as possible;
- the best available low noise front end amplifiers to improve instantaneous sensitivity;
- observing conditions as stable as possible in order to allow long time integrations ($10^4 \div 10^5$ s);
- sky coverage $> 80\%$.

Other experiments are currently attempting to measure CBR polarization from ground (see for example Sironi et al., 1998 (4) and Keating et al., 1998 (5)) but with limited sky and frequency coverage. Also the measurements technique is quite different from that adopted in SPOrt, where dedicated components are used to optimize the experimental configuration. Most challenging aspects of the SPOrt project, apart from the extremely short realization time imposed by the ISS schedule, can be summarized by:

- realization of an antenna system suitable to separate the two circular components of the observed radiation with low (< -45 dB) cross-polarization;
- realization of a radio-polarimetric chain able both to improve the total unpolarized component rejection up to -70 dB and to reduce as much as possible the total contribution of systematics (drift, offsets, $1/f$ noise);
- realization of an overall experiment structure suitable to fit the ISS constraints (mechanical, thermal, observational).

THE SPORT EXPERIMENT

Following the above ideas the SPOrt design is based on four separate polarimeters at 22, 32, 60 and 90 GHz characterized by:

1. Corrugated Feed Horn Antennas (CFHA) with $HPBW = 7°$, extremely low sidelobes and cross-polarization;
2. Iris Polarizer (IP) followed by an Orthomode Transducer (OMT), to provide separate Left Hand Circular (LHC) and Right Hand Circular (RHC) components;
3. two low noise Phase Switched Radiometric Chains (PSRC);
4. Analog Correlation Unit (ACU);
5. Phase Synchronous Detection Unit (PSDU);
6. Post Detection Unit (PDU).

The signal collected by the antennas is divided into its two circularly polarized components, LHC and RHC, by both the IP and the OMT. The OMT provides then two outputs, which are independently amplified by two PSRCs and then correlated by the ACU in order to get outputs proportional to both Q and U Stokes parameters. In this way it is possible to have an instantaneous full characterization of the linear polarization of the observed sky.

From a bandwidth point of view, a good sensitivity calls for a large absolute value but relatively small with respect to the central frequency to avoid degradation of the component performance versus the bandwidth. For these reasons the SPOrt radiometers use RF bandwidths of 10%, avoiding a down conversion and correlating the signals at RF level. The capability to reach the long term sensitivity at μK level relies on two main characteristics of the radiometers: i) noise temperature as low as possible as well as non gaussian noise at μK level (after off-line integration); ii) the best characterization of performances so that all systematic effects can be removed. The correlation technique, in fact, should provide Q and U Stokes parameters free, in principle, from the $1/f$ noise coming from the low noise amplifiers as well as from uncorrelated gain variations of the two receiver channels. Moreover the modulation of the RF signal helps to remove undesired effects such as output drifts, flicker noise coming from post detection electronic section and spurious cross-polarization from non ideal devices. Taking into account all these aspects a schematic block diagram of each SPOrt channel is shown in Figure 1. It could be divided into three principal parts: the antenna system, the low noise PSRC, the correlation-detection-demodulation section (ACU + PSDU).

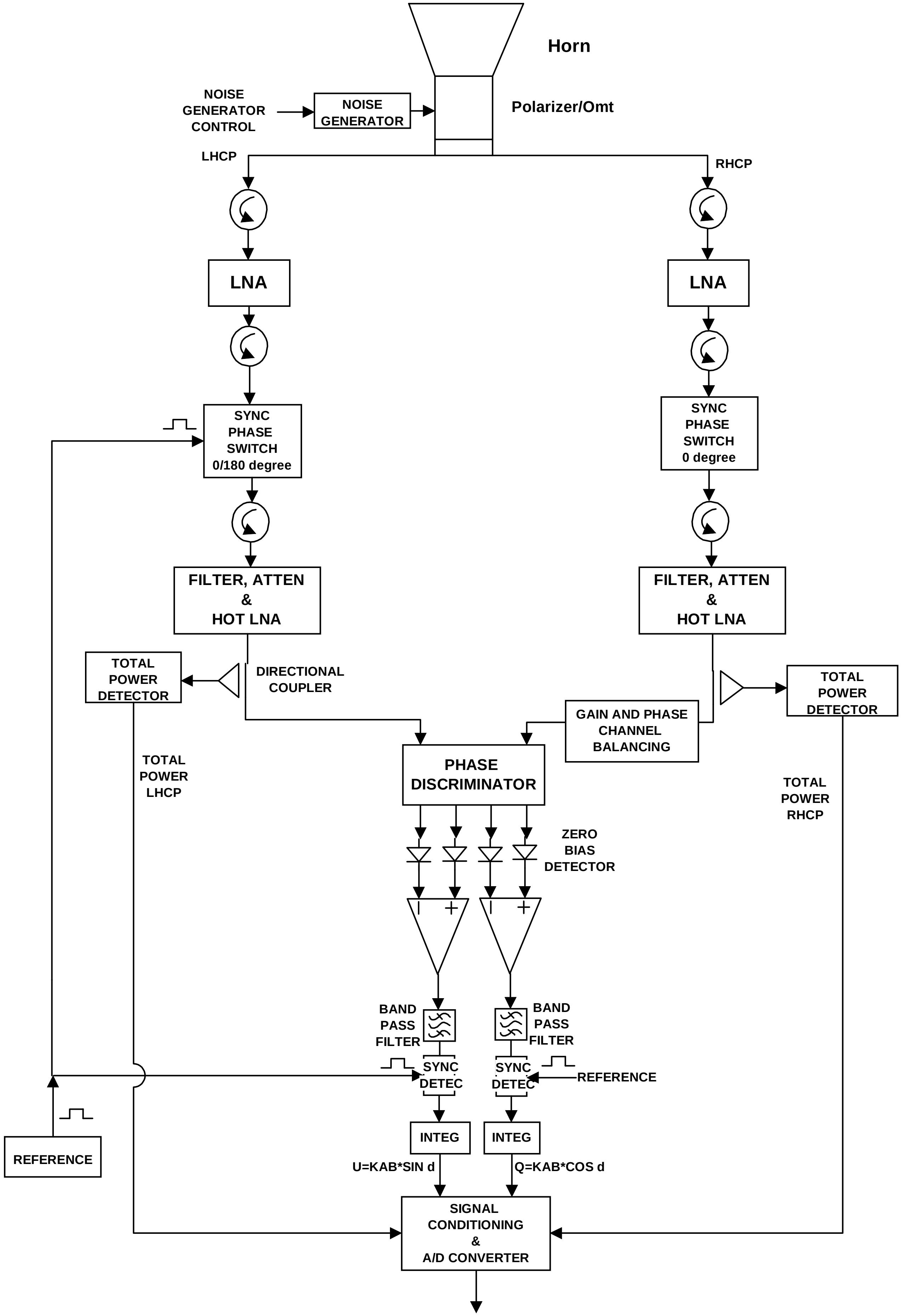

FIGURE 1. Schematic block diagram of the SPOrt radiometers.

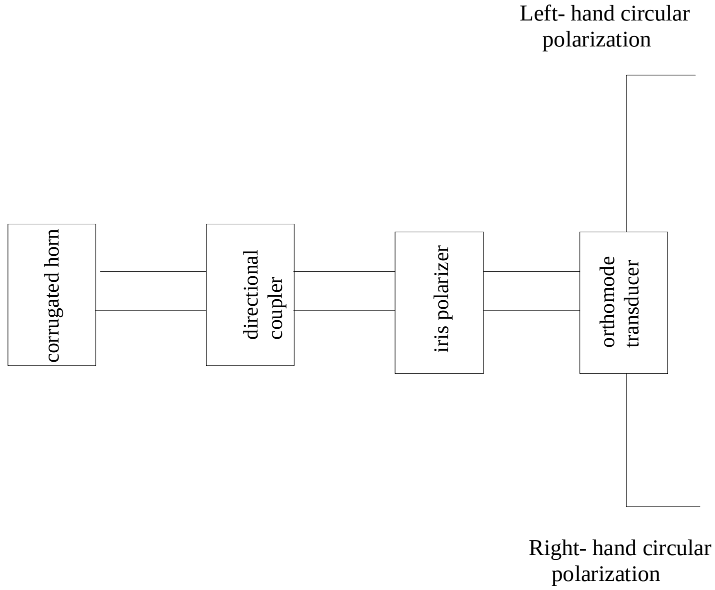

FIGURE 2. SPOrt antenna system.

Antenna system

The antenna system will include: CFHA, IP, OMT and a coupling device (e.g. a waveguide with directional coupler) to inject a known noise calibration signal (see Figure 2). All these parts must be included in a unique design to optimize overall characteristics.

The most relevant SPOrt antenna system specifications at all frequencies can be summarized in: a) 10% bandwidth, two circular polarizations and $7°$ $HPBW$ beamwidth, b) an insertion loss < 0.5 dB, c) a return loss < -25 dB, d) a sidelobe level < -60 dB and e) a cross polarization level < -45 dB. Figure 3 shows an example of the current status of the antenna system design for SPOrt. Both the copolar and the cross-polar pattern of the 90 GHz feed of COBE/DMR are also shown for comparison.

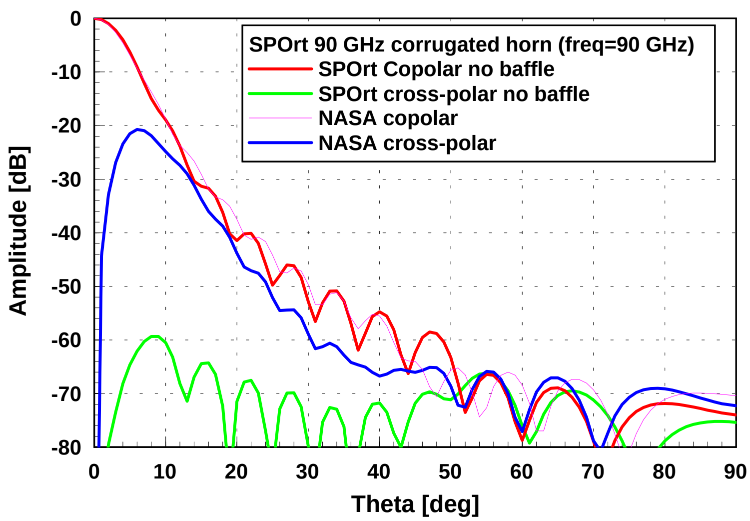

FIGURE 3. SPOrt antenna pattern compared to COBE/DMR.

Low Noise PSRC

Low Noise Amplifiers (LNA) represent the most critical component, together with the insertion loss of the antenna system, to obtain instantaneous sensitivities < 2 mK $\mathrm{s}^{\frac{1}{2}}$ as required to meet SPOrt scientific goals (3). Two LNA stages are needed (for a total ~ 70 dB gain): the first one will be cooled at 80 K and the gain must be enough to mask the noise of the following components; the second amplifier, together with the rest of the receiver, is included in the warm unit (~ 300 K). The $(0° - 180°)$ phase switch is part, together with the PSDU, of the lock-in chain, which has the task to minimize gain drifts, offsets, $1/f$ noise generated inside the loop. This method will allow also to remove the cross-polarization generated in the HPD as well as part of the spurious effect due to the unpolarized component (see sections below).

The polarimetric unit

The polarimetric unit is essentially the ACU and includes (see Figure 1):

- Hybrid Phase Discriminator (HPD);
- square law detectors;
- differential amplifiers plus integrator.

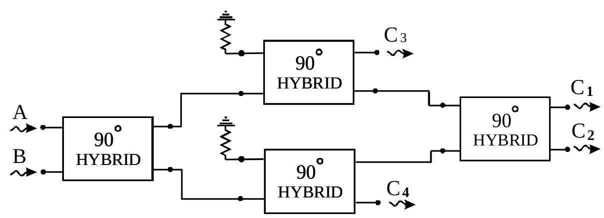

FIGURE 4. Equivalent circuit of SPOrt HPDs.

The HPD is a passive microwave circuit consisting of four Hybrid directional couplers and one 90° differential phase shifter, that processes the signal in order to have four outputs. The HPD equivalent circuit is shown in Figure 4. After square law detection the four outputs:

$$
\begin{aligned}
V_1 &= |c_1|^2 &= \tfrac{1}{4}\left[|A|^2 + |B|^2 - 2\Re\{AB^*\}\right] \\
V_2 &= |c_2|^2 &= \tfrac{1}{4}\left[|A|^2 + |B|^2 + 2\Re\{AB^*\}\right] \\
V_3 &= |c_3|^2 &= \tfrac{1}{4}\left[|A|^2 + |B|^2 + 2\Im\{AB^*\}\right] \\
V_4 &= |c_4|^2 &= \tfrac{1}{4}\left[|A|^2 + |B|^2 - 2\Im\{AB^*\}\right]
\end{aligned}
$$

(where A and B represent previously called LHC and RHC after amplification) are then properly differentiated to get two outputs

$$\Re\{AB^*\} \equiv |AB|\cos\phi \tag{1}$$
$$\Im\{AB^*\} \equiv |AB|\sin\phi \tag{2}$$

which after integration will give time averaged values directly related to Q and U Stokes parameters.

The HPDs working at the four SPOrt frequencies will be especially designed and manufactured with waveguide technology for the SPOrt experiment because they are not commercially available. To optimize performances, an integrated waveguide solution will be adopted. In particular, the coupling between the rectangular waveguides of the directional couplers and the phase delay of the phase shifter will be obtained by using a perforated septum placed on the E-plane. In this way i) the coupling between waveguides will be in the H-plane and ii) the waveguides are 5-folded in the E-plane to obtain a compact solution which has been called "5-floor-HPD". The whole configuration was studied to be manufactured by electroerosion technology so that stringent tolerances can be maintained.

At the four frequency bands, both hybrid directional couplers and phase shifters, must have a return loss of 40 dB, an isolation of 40 dB, the balance function ratio less than 0.1 dB and a phase error of $\pm$ 0.1 deg. The specifications will be maintained in the 10% bandwidth. Inside each device will be also integrated a filter to properly shape the input band and a directional coupler to split part of the incoming power for the total power detection (see Figure 1). One of the most important specifications for the HPD is the rejection of the unpolarized signal coming from the sky, such as that due to the CBR ($\sim$ 3K). This unwanted contribution is eliminated by the difference carried out by two differential amplifiers. For this reason, it is very important to maintain a high level of symmetry in the whole device. It can be shown that the cross signal generated from the devices inside the modulation loop (see Figure 1) is thrown away because of the modulation technique. This technique is also adopted to minimize both characteristics dispersion and $1/f$ noise coming from other components (i.e. diodes and differential amplifiers, etc ...).

THE PROBLEM OF THE SPURIOUS POLARIZATION

The output expressions in the previous section are only an idealization. In the real case, due to cross-polarization effects, part of the unpolarized incoming radiation will appear as polarized. In addition, the two Stokes parameters Q and U will pollute each other so that a practical expression of the correlated outputs should be:

$$Q_t = Q + a\,U + b\,|A|^2 + b\,|B|^2 \tag{3}$$
$$U_t = U + c\,Q + d\,|A|^2 + d\,|B|^2 \tag{4}$$

where a, b, c and d are coefficients to be measured during antenna characterizations. The terms $|A|^2$ and $|B|^2$ are due to the cross-polarization generated in the antenna system. After PSDU, only cross-contributions from the antenna system will remain, and very much effort is currently devoted to minimize and characterize such residuals. Moreover the coefficients in the equations above are $\ll 1$ so the term $a\,U$ in equation (3) and the term $c\,Q$ in equation (4) are negligible with respect to Q and U respectively. Thus it can be written:

$$Q_t = Q + b\,|A|^2 + b\,|B|^2 \tag{5}$$
$$U_t = U + d\,|A|^2 + d\,|B|^2 \tag{6}$$

The coefficients b, d represent the cross-polarization of the antenna system.

It can be shown that the coefficients b, d are due to non-orthogonality between LHC and RHC. In other words two components elliptically polarized, but rigorously orthogonal, do not generate spurious correlated signals. In particular, as far as the spurious correlated signals are concerned, the parameter that must minimized is not the cross-polarization level of the antenna system but rather the following expression:

$$\frac{4}{\pi \Delta\theta^2_{-3dB} \Delta\omega} \int_{\Delta\omega} \int_0^{\pi} \int_0^{2\pi} \underline{h}_A\left(\omega,\theta,\varphi\right) \cdot \underline{h}^*_B\left(\omega,\theta,\varphi\right) sin\theta d\varphi d\theta d\omega$$

where $\Delta\theta_{-3dB}$ is the HPBW of the antenna, $\Delta\omega$ is the bandwidth and $\underline{h}_A$ ($\underline{h}_B$) is the vector radiation pattern (it has components in θ and φ directions) corresponding to the port A (B) of the Orthomode Transducer, normalized to its maximum value. As a comment of the above expression, one can observe that the scalar product between the two vectors $\underline{h}_A$ and $\underline{h}_B$ which describe the radiation field, is weighted by the radiation pattern through the integration on the $(\theta - \varphi)$ directions and cancellation effects may occur. Thus, the optimization of the instrument design with respect to the orthogonality between the two polarizations of the antenna allows to reduce the level of the spurious correlated signal. Usual values for b, d will range around 0.001, so an offset of few mK will appear at the output for each on board integration time. An accurate characterization and stability of this systematic effect is needed to allow final sensitivities at μK level.

THE EXPECTED PIXEL SENSITIVITY

The orbit of the ISS was calculated (with some assumptions on the flight parameters not yet specified by NASA) to simulate the path of the SPOrt radiometers across the sky and to compute total integration time versus sky position. This was done assuming the radiometers pointing at the zenith of the ISS Express Pallet even if the developed code can take into account any inclination with respect to this direction.

The orbit has a quasi-sinusoidal shape in the RA–DEC plane and its amplitude is equal to the inclination of the ISS orbit, $51\overset{\circ}{.}6$. In fact the precession effect translates into an RA shift of 360°/(Prec. period)/(Orbits per day) $= 0\overset{\circ}{.}32$ per orbit. Such an orbit has the following characteristics: the same point is scanned $\sim 2 \times 7^\circ / 0\overset{\circ}{.}32 = 45$ times per precession period; the sky portion scanned by SPOrt in half and all the precession period are $\sim 70\%$ and $\sim 82\%$ respectively.

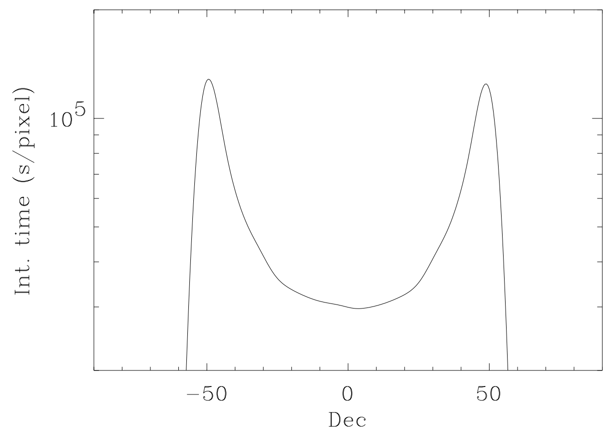

FIGURE 5. Integration time across the sky vs declination.

The expected integration time is shown in Figure 5 for the whole observed declination interval. The map shows symmetry along the $\delta = 0$ axis and peaks at $\pm 51\overset{\circ}{.}6$, the values of integration time do not depend on the right ascension coordinate. Highest integration times/pixel are far from the celestial equator because of:

1. a slower motion in the declination axis approaching the $\pm 51\overset{\circ}{.}6$
2. the $1/\cos\delta$ beam deformation: meridians are closer each other at high declinations and the beam width seems larger, so the number of independent pixels is lower.

The sensitivity for each pixel was then calculated assuming that the radiometer equation

$$\Delta T_{\rm rms} = \frac{\sqrt{2} \cdot T_{\rm sys}}{\sqrt{\Delta\nu \cdot \tau}}$$

holds for the expected integration time, where $\Delta\nu$ is the bandwidth (10% of ν), $\Delta\tau$ is the integration time, $T_{\rm sys}$ is the system temperature and the factor $\sqrt{2}$ comes from the radiometer's configuration (correlation radiometer). Due to various effects, such as stray-light from solar panels, Sun and Moon entering into the sidelobes, shuttle operations and so on, it would not be possible to use the full SPOrt data set. As a conservative estimate we consider a 50% observing efficiency. Basic data on the expected final sensitivity for the single pixel and for the full sky are reported in Table 1; $T_{\rm sys}$ are computed from simulations based on preliminary SPOrt specifications and available components. Current development activities would indicate that some margin of improvement is still left.

CONCLUSIONS

The SPOrt project, after its selection by ESA (end 1997), is currently under phase B. Part of the 1999 activity will be devoted to build breadboards at 22 and 90 GHz in order to make engeneering tests before to proceed towards the Flight Model realization (payload delivery to ESA/NASA is by the end of year 2000).

TABLE 1. SPOrt expected sensitivity after 1.5 yr lifetime.

ν (GHz)	T_{sys} (K)	ΔT_{rms} (mK $\mathrm{s}^{\frac{1}{2}}$)	P_{pix} (μ K)[a] min	max	P_{rms} (FS)[b] (μK)
22	66	2.0	7.85	16.3	0.52
32	82	2.0	8.09	16.8	0.54
60	115	2.0	8.57	17.8	0.57
90	167	2.0	9.82	20.4	0.65

[a] Computed for 50% efficiency and 10% frequency bandwidth.
[b] Full sky (FS) coverage is 81.7% of 4π sr, including 662 pixels.

The very tight ISS schedule have forced the SPOrt team (Scientific collaboration plus Industrial consortium) to adopt a new philosophy for the project realization, which may be resumed as "faster, better and cheaper". Since SPOrt represents the first European scientific payload at microwave frequencies, it will be also a unique opportunity to test technological solutions that could be the base for future and more ambitious CBR space project. SPOrt, in fact, shall begin to operate just after the MAP satellite (2001) and before PLANCK (2007), so playing an important bridging role between NASA and ESA CBR space programs. PLANCK-LFI may also benefit of some technological solution, that can be tested in-flight by using SPOrt opportunities as well as of scientific results especially related to galactic foregrounds. SPOrt would play also an important role to promote technological developments that can be used for ground application in Radioastronomy at short times.

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