THE SKY POLARIZATION OBSERVATORY (SPOrt*) TWO YEARS LATER

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ABSTRACT

The current design of the Sky Polarization Observatory (SPOrt) experiment is presented. SPOrt scientific objectives are shortly discussed as they have been revised during two years of activities since the original idea of SPOrt was presented. Major changes regard observed frequency range, covering now the 22–90 GHz interval, as well as the number of channels, which has been increased to four. The new configuration adds the measurement of the Cosmic Microwave Polarization to the SPOrt scientific goals.

Key words: polarimetry; cosmology; space science; Cosmic Microwave Background; Galaxy.

1. WHY CHANGE?

The first SPOrt idea (Cortiglioni et al. 1996, hereafter SPOrt-1) was based on the need of a better knowledge of the Galactic foreground polarization, which is completely unexplored at frequencies higher than 1.4 GHz. Maps at various lower frequencies were made by Brouw and Spoelstra (1976). Uyaniker et al. (1998) more recently observed both continuum and polarization of a strip of $\pm 20^\circ$ around the galactic plane at 1.4 GHz. Only regions near the galactic plane have been mapped in linear polarization at 2.695 GHz (Junkes et al. 1987) so far and they are practically useless for foreground subtraction in full sky measurements of the Cosmic Microwave Background.

However the scenario of the CMB measurements has changed after SPOrt was originally proposed in 1996. Today the interest for the CMB polarization from space has grown: both MAP (a NASA space mission scheduled for 2001) and PLANCK (an ESA space program expected around year 2007), planned for measurements of the CMB anisotropies with unprecedented high degree of accuracy, include among their objectives the search for polarization.

Both experiments, being designed to measure CMB anisotropies at small angular scales are expected to

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reconstruct the CMB angular power spectrum up to high harmonic orders, $l \sim 10^3$, so that many parameters of current cosmological models can be constrained. It has been noticed however that parameter degeneracies arise from anisotropy data alone (Efstathiou & Bond 1998). Polarization data in particular can break the degeneracy between the secondary-ionization redshift and the gravitational-wave spectrum (Kinney 1998). The secondary ionization of the cosmic medium is a long standing cosmological problem to which SPOrt seems suitable to provide a solution. Its beamwidth is especially apt to detect polarization harmonics with $l \sim 10$–20, which according to current reionization models are excited at levels of a few μK or tenths of μK (Ng & Ng 1996, Sazhin & Toporenskii 1998, Fabbri et al. 1998). The goal of detecting cosmological polarization looks quite plausible in the 60–90 GHz range, but a careful spectral analysis will be required to discriminate foregrounds.

Multifrequency full sky polarization measurements of Galactic synchrotron radio emission at very high frequencies (where Faraday rotation and depolarization is negligible) to be made by SPOrt allow to study the radio spectrum of the total Galactic synchrotron radio emission (the knowledge of this spectrum helps one to separate different components of the Galactic radio emission and the CMB), as well as to obtain the valuable information on the energy spectrum of relativistic electrons and the structure of the interstellar magnetic field. Space observations greatly improve the quality of polarization measurements because ground based measurements are affected by tropospheric, ionospheric and by partly linearly polarized (not constant) ground radiation.

2. A NEW EXPERIMENT'S PHILOSOPHY

The International Space Station Alpha (ISSA) is very different from a free-flyer. It is rather a facility which can accommodate a variety of experiments in different fields outside the Earth atmosphere. A possibility for European scientists to access ISSA came from the ESA Announcement of Opportunity for Externally Mounted Payload (1997). The SPOrt team took this opportunity and prepared his proposal taking into account that participation to the ISSA program means a new experiments philosophy based on:

- small payloads;
- short realization times;
- limited financial resources;

which also implies:

- restricted objectives;
- use of state of the art technologies;
- synergetic use of both scientific and industrial resources;
- no scientific overlaps with other space missions.

3. WHICH CHANGES?

Major changes are summarized in Table 1, where the 2^{nd} an the 3^{rd} columns report basic instrumental characteristics of SPOrt-1 and SPOrt-2 (current design) respectively. Major changes regard:

- frequency coverage;
- number of channels;
- front-end Low Noise Amplifiers (LNAs);
- cooling;
- antenna beam width (FWHM);
- pointing.

Let us now discuss separately these points:

3.1 Frequency coverage: we originally proposed the 10–30 GHz range mainly because we were interested in measurements of the linear polarization of the diffuse galactic emission and decided to rely on commercially available components. But the scenario changed very rapidly and the opportunity to attempt measurements of the CMB Polarization convinced us to extend the frequency coverage up to 90 GHz. Moreover the limited room available on the ISSA Express Pallet Adapter (EXPA) forced us to eliminate the 10 GHz channel because of the physical dimension of the horn.

3.2 Number of channels: Within the 20–90 GHz range we chose regularly spaced channels (see section 5) to allow a recognition of the various contribution to the sky signal, dominated by the galactic emission at low frequency and by the CMB plus dust emission at high frequencies. Current frequency channels are also close to those already foreseen by other space projects (MAP and PLANCK) for easy comparison with anisotropy data expected to come from them.

3.3 Good Low Noise Amplifiers (LNA) at 10–30 GHz are of common use in radioastronomy, so that their availability was quite sure when SPOrt-1 was proposed. The current design (SPOrt-2) requires critical LNAs for space applications that are not easily available at frequencies higher than ~ 40 GHz, or if they are, have quite poor noise figures.

3.4 The cooling of the SPOrt-1 front-end, (essential to keep the system temperature sufficiently low to reach the sensitivity required for detection of μK signals) was supposed to be obtained passively. Further investigations on the ISSA environment showed however that passive cooling was insufficient to let LNAs operate at best conditions. SPOrt-2 was therefore designed with an active cooling system, which is expected to keep LNAs at temperatures ≤ 80 K.

3.5 The SPOrt-1 antennae had $FWHM = 4°$–$6°$ (2° with lens horns), but the long time necessary to develop them and uncertainties about the noise produced by lenses convinced us to adopt a larger beam. It has been decided to give maximum priority to realize feed horns with extreme performances in terms of sidelobes and cross-polarization. The current value

Table 1. A summary of SPOrt-1 (2^{nd} column) and SPOrt-2 (3^{rd} column) main characteristics.

Main Scientific objective	To map Stokes parameters (I, Q, U) over extended sky regions on degrees angular scale	To map Stokes parameters (I, Q, U) over extended sky regions on degrees angular scale
Working frequencies	10 GHz – 20 GHz – 30 GHz	22 GHz – 32 GHz – 60 GHz – 90 GHz
Detector type	HEMT (Param.) correlation radiometers polarimeters	HEMT correlation radiometers polarimeters
Detector cooling	Passive at $\sim$ 100K	Active at $\sim$ 80K ($\sim$ 250 K for feeds)
Angular resolution(HPBW)	4°, 6° (2° with Lens Horns)	7°
Antennas	Corrugated (Lens) Horns	Corrugated Feed Horns
1 year sensitivity (1σ)	$\sim$ 10 μK	$\sim$ 1 μK (full sky, 1.5 years)*
Sky coverage with pointing capability	about 100 %	No pointing capability
Sky coverage with no pointing capability (1 year)	$\sim$ 80 %	$\sim$ 80 %
Pointing capability	very useful but not strictly necessary	No pointing capability

* 50% efficiency

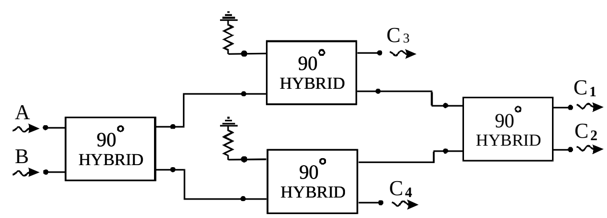
of $FWHM = 7°$ looks reasonable for both manufacturing and scientific objectives.

3.6 Pointing: SPOrt-1 included a Coarse Pointing Device (CPD) provided by ESA. Subsequently this device was eliminated by ESA to leave room for other payloads which had to be accommodated over the EXPA. as a consequence SPOrt-2 does not have any pointing device and it will observe in sky scanning mode pointing the zenith direction. Nevertheless the pointing accuracy will play an important role.

4. THE CURRENT EXPERIMENTAL DESIGN

The current design of SPOrt has been carried on taking into account the same criteria of simplicity, short term feasibility and flexibility which drove the original SPOrt-1 idea, as well as the extreme sensitivity (detection of signals close to 1 μK in 18 months) required by the new cosmological goal: search for a degree of CMB linear polarization at level of a few parts on 10^6 (Cortiglioni et al. 1998). SPOrt is now a set of four identical correlation receivers respectively tuned at 22, 32, 60 and 90 GHz with 10% of bandwidth, fed by quasi-geometrically scaled corrugated horns with an $FWHM = 7°$ looking directly the sky at the ISSA zenith. The block diagram of a single radiometer is shown in Figure 1.

The horn plus the iris polarizer and the Orthomode Transducer (OMT) splits the incoming radiation (unpolarized plus polarized) in two components circularly polarized in opposite directions. These signals are fed in two identical chain where LNAs, amplify the signals to be injected in the correlation unit. This unit, a combination of a passive Hybrid Phase Discriminator (HPD, Figure 2), two differential amplifiers and a time integrator, averages out all signals providing two outputs proportional to the Stokes parameters U and Q, which describe the linearly polarized fraction of the radiation entering the horn mouth.



$$V_1 = |c_1|^2 = \frac{1}{4}\left[|A|^2 + |B|^2 - 2\Re\{AB^*\}\right]$$

$$V_2 = |c_2|^2 = \frac{1}{4}\left[|A|^2 + |B|^2 + 2\Re\{AB^*\}\right]$$

$$V_3 = |c_3|^2 = \frac{1}{4}\left[|A|^2 + |B|^2 + 2\Im\{AB^*\}\right]$$

$$V_4 = |c_4|^2 = \frac{1}{4}\left[|A|^2 + |B|^2 - 2\Im\{AB^*\}\right]$$

Figure 2. Equivalent circuit of the Phase Discriminator.

For an ideal correlator this system is sufficient to detect the polarized signal. Considering however the very low level of the CMB polarization, it is expected from a real system spurious outputs comparable or greater than the polarized signal SPOrt is looking for. To reject these spurious signals that limit the

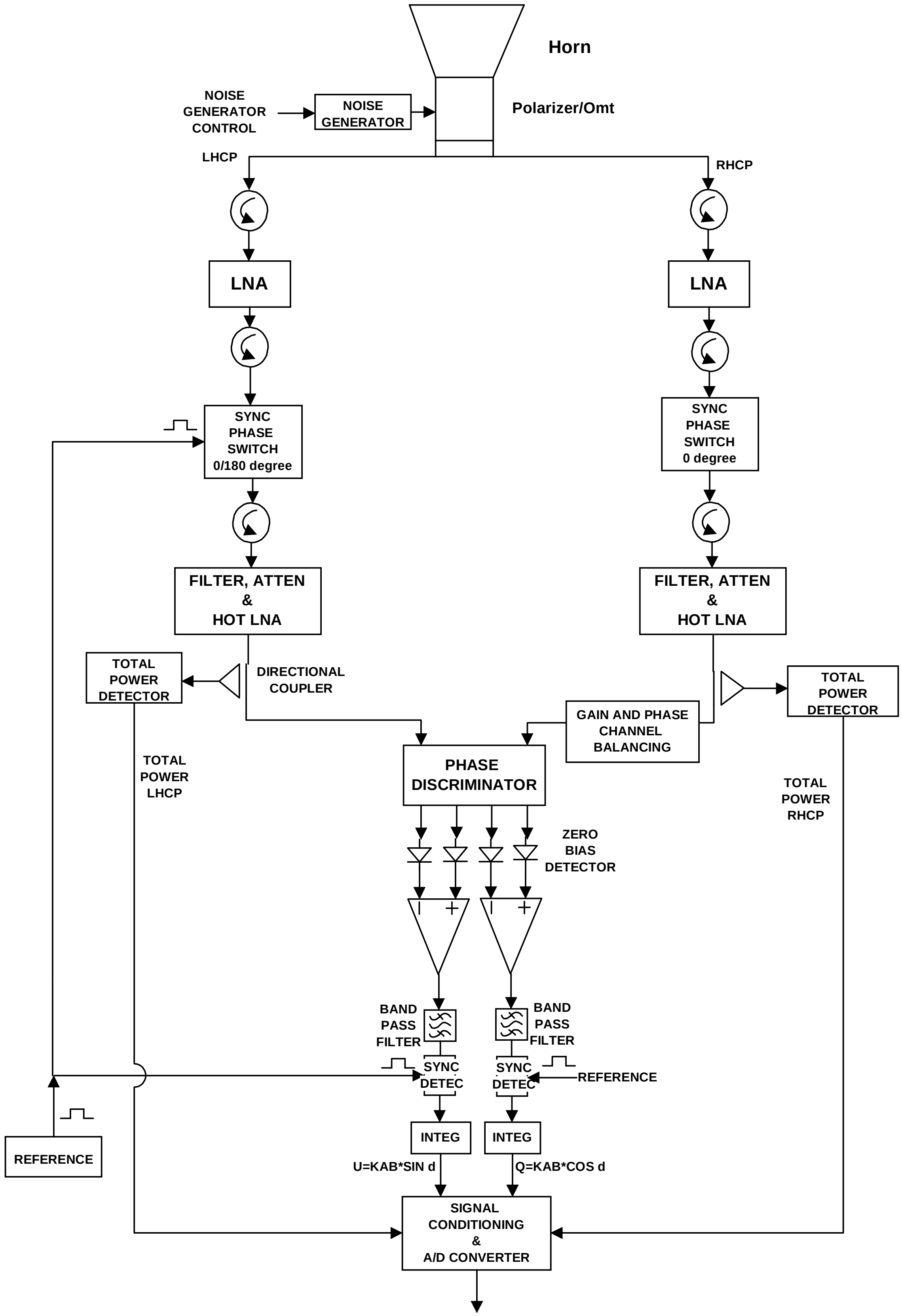


Figure 1. SPOrt block diagram.

sensitivity, the correlation unit has been included in a system made of a (0°–180°) phase modulator and a phase sensitive detector (lock-in) which eliminate both off-sets and the low frequency 1/f noise. The sensitivity (minimum detectable signal) for a correlation radio-polarimeter is given by (see for instance Krauss 1970):

$$\Delta T_{RMS} = T_{sys}\sqrt{2 \cdot \frac{(1+\beta)}{t_{int}\Delta f}}$$

Where T_{sys} is the (total) system noise temperature, t_{in} is the integration time, Δf is the RF bandwidth, β is a coefficient which accounts for system gain instabilities and phase noise (both to be minimized). Integration times of $10^4 - 10^5$ s are necessary to reach the goal sensitivity (see Figure 3 and Tables 1, 2). This is done through off-line analysis. Very high system stability as well as good pointing reconstruction are required to allow superposition (a posteriori) of data arriving from the same spot on the sky observed at different times. Continuum system monitoring and internal calibration are obtained by injection in the throat of the horn (before the iris polarizer and the OMT) of a known noise signal. A complete discussion of a similar correlation receiver is given in Sironi et al. (1998). Table 2 reports the expected sensitivity for each SPOrt channel.

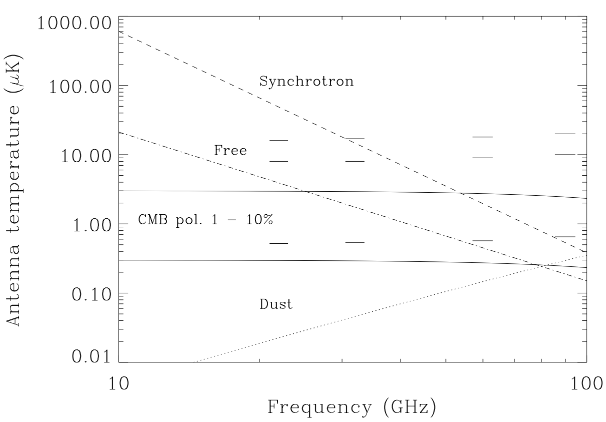


Figure 3. Expected foreground and CMB polarized emission in the SPOrt frequency range. Horizontal ticks refer to (from top to bottom) minimum and maximum pixel sensitivity, and full sky (averaged over all sky pixel) sensitivity. All sensitivities are calculated assuming 50% efficiency.

5. RELATED SCIENTIFIC AND TECHNOLOGICAL ACTIVITIES

5.1. Scientific Activities

Recent technological developments were accompanied by studies aimed at the exploitation of the new configuration. Since the current design allows us to consider the CMB polarization as a new scientific goal for SPOrt, we need to study the important problem of optimal foreground separation. In CMB experiments foregrounds generally come both from our Galaxy and extragalactic sources lying along the line of sight, but the beamwidth of the SPOrt radiometers will be large enough for the extragalactic point-like sources contribution to be negligible.

Table 2. Overall system temperature, instantaneous sensitivity, long term expected sensitivity (average) and full sky sensitivity (averaged over all pixels) for each SPOrt-2 channel.

Frequency (GHz)	T_{sys} (K)	ΔT_{RMS} (mK s$^{-\frac{1}{2}}$)	Average RMS/pixel (μK)	Full Sky sensitivity (μK)
22	65	2	13.4	0.52
32	82	2	13.8	0.54
60	119	2.2	14.7	0.57
90	168	2.5	16.8	0.65

Galactic emission can be related to three different physical processes: i) synchrotron emission is produced by relativistic electrons moving in the Galactic magnetic field. In terms of antenna temperature, $T_{Syn} \propto \nu^{-S}$ with $S = 2.6 \div 3.2$ depending on the spatial position. Synchrotron emission has an intrinsic linear polarization of about 75% for an ordered and aligned magnetic field, but irregularities in the magnetic field reduce this value to $\lesssim$ 30% (Spoelstra 1984). ii) Free-free (Bremsstrahlung) emission arises from interaction between free electrons and ions in a plasma. Its spectral dependence is accurately described by $T_{FF} \propto \nu^{-F}$ with $F = 2.13 \div 2.16$, rather insensitive to spatial position and frequency. Free-free emission can be polarized via Thomson scattering within optically thick plasma regions (Keating et al. 1998). We set an upper limit of 5% on its polarization percentage although at microwave wavelength H II regions are to be considered optically thin. iii) Dust emission has thermal origin and, following Wright et al. (1991), can be modeled with a mixture of two graybodies with emissivities ν^{-2}, so that the antenna temperature $T_{Dust} \propto [B_\nu(20.4\ \mathrm{K}) + 6.77 B_\nu(4.77\ \mathrm{K})]$. Dust emission can be polarized (provided dust grains are aligned by the Galactic magnetic field) to a level of about 10% (Draine & Lazarian 1998). Estimates for the above polarized components are reported in Figure 3.

The separation of the contributions to polarized signals is based on the different spectral and spatial behaviors of foregrounds and CMB; multifrequency observations thereby play a fundamental role. We performed a preliminary analysis taking advantage of Dodelson's (1995) analytical formalism. This formalism allows us to estimate the experiment effective sensitivity for any signal component after subtraction of the other contributions. The sensitivity for CMB is given by $\sigma^2_{CMB} = FDF^2\sigma^2_{ch} + \sigma^2_{shape}$ where σ_{ch} is the instrumental sensitivity, and the other two parameters depend on the intensity and spectral shape of the foregrounds. The foreground degradation factor FDF describes the experiment sensitivity after removal of foregrounds with perfectly known spectral shapes; σ_{shape} takes into account errors which arise from uncertainties in the spectral shapes or from neglecting the contribution of some foreground component. The best effective sensitivity for an experiment is reached by a proper balance of two contrasting effects, since increasing the number of fitted foregrounds makes σ_{shape} smaller but FDF larger. Table 3 reports the values of the above parameters for different treatments of SPOrt output. The computations assume polarized intensities of 18 μK and 2 μK for synchrotron and free-free, respectively, at 30 GHz, and the assumed spectral slopes are $S = 3.2$ and $F = 2.15$; dust polarized emission is normalized to 1 μK at 200 GHz. When the number of channels used for the foreground fits is 3 (see the first column in Table 3), the high frequency channel is not used. The second and third column specify whether free-free and dust emission are fitted. Clearly the best results for the SPOrt experiment are found when free-free and dust emission are not fitted (so that $\sigma_{shape} \neq 0$). Using four channels we have $FDF = 1.38$ and $\sigma_{shape} = 0.61$. Using SPOrt total-sky coverage (Figure 4), the instrumental sensitivity (Table 2) and treating σ_{shape} as a systematic error, from the above numbers we get $\sigma_{CMB} = 0.73$ μK as the effective sensitivity for CMB after foreground subtraction. If the 4-th channel is not used in the fit, we have a just slightly larger value, $\sigma_{CMB} = 0.80$ μK.

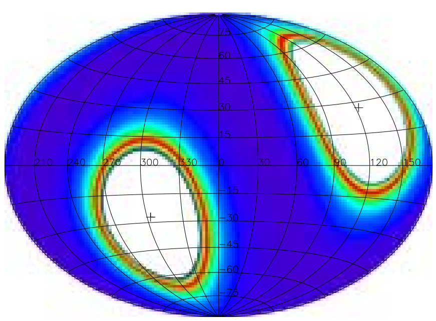


Figure 4. The sky that can be seen from the ISSA observing towards the zenith (82%). Grey scale represent the integration time (regions around both celestial poles cannot be observed).

We should emphasize that the above sensitivity limits are computed by considering the σ_{shape} derived from a single-pixel analysis as completely systematic, and neglecting any information that may come from spatial correlations. The temperature Galactic foreground is spatially correlated more than the CMB signal (Kogut et al. 1996). This appears to be true also for polarization according to current models (Sethi et al. 1998). Figure 5 compares the spherical harmonic spectra for two CMB reheating models with the 90 GHz Galactic dust spectrum. The reported coefficients dimensionlss P_l (expectation values of squared harmonic strengths multiplied

Table 3. Foreground degradation factor and effective sensitivity for different treatments of SPOrt output.

Channels #	FF	$Dust$	FDF	σ_{shape} (μK)	σ_{CMB} ($\leq$) (μK)
4	YES	YES	8.80	0.00	2.52
4	NO	YES	2.76	0.77	1.10
4	NO	NO	1.38	0.61	0.73
3	NO	NO	1.54	0.64	0.80
3	YES	NO	63.60	0.24	1.16

by $l(l+1)/2$) are good estimates of the squared fractional polarization at angular scales $\sim 180°/l$, and the steeper increase with l for the CMB curves implies smaller spatial correlation. The study of spatial correlations is expected to reduce the impact of σ_{shape} so that the final sensitivity is essentially determined by noise and FDF. We can conclude that, according to the presently planned configuration, the full-sky effective sensitivity to CMB polarization can be estimated around 0.5 μK; this number takes into account a 50% efficiency, removal of a belt around the Galactic plane and the separation of Galactic foregrounds. The above sensitivity is sufficient for a first estimate of the secondary ionization redshift, or equivalently of the Thomson-scattering optical depth of the ionized medium. Many models appearing in the literature assume reionization optical depths τ_{ri} of order unity. An upper limit of $\tau_{ri} = 0.7$ can be derived from computations of De Bernardis et al. (1997), and modeling of ionizing sources suggest values of order 10^{-1} (Haiman & Loeb 1997). We performed extensive computations of polarization spectra in current cosmological models, using routines of the SPOrtLIB library which is now under development (Fabbri et al. 1998). According to the results, models with $\tau_{ri} = 0.7$ give a 7° rms polarization well above the 0.5 μK level, while models $\tau_{ri} = 0.1$ are typically just around the limits of SPOrt capabilities. Therefore we expect SPOrt to be able to detect the CMB polarization or at least set very stringent limits on the strength of the secondary ionization.

5.2. Technological Activities

The overall design of the radiometric part is one of most demanding activities, mainly because of the time schedule which does not allow so much developing work. Much effort has been put to match scientific requirements with available components in the best way. Much engineering effort has been dedicated to develop Phase Discriminators at the level required by SPOrt. Such devices, in fact, are well known (see an example in Figure 2), but the available ones i) do not cover the SPOrt frequency range and ii) do not have the needed performance especially in terms of channel isolation and space qualification. Such devices will be available for both scientific and indus-

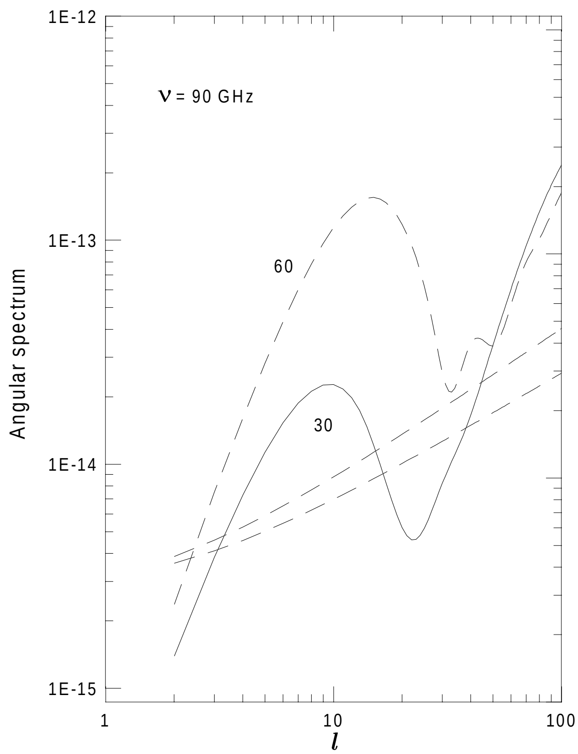


Figure 5. Polarization spectra from CMB and dust. The CMB curves refer to standard CDM models with a scale-invariant density perturbation spectrum, and are labeled by the corresponding values of the reionization redshift. The dust spectrum is derived from Sethi et al. (1998) after scaling to 90 GHz.

trial future applications in space. Also feed horn antenna's design as well as thermal studies are taking much effort. The challenging technological activities related to the SPOrt needs could be summarized as:

- using the state of the art low noise amplifiers up to 90 GHz;
- HPDs, never made at these high frequencies, to provide a very high bandwidth analog polarimeter in a compact, reliable, performing; passive device
- a relatively new architecture of a radiometer, by using phase modulation technique, usually not used in radioastronomy;
- realization of feed systems at the ultimate performance with regard to the sidelobes level and cross-polarization.

All of this experience will have a very interesting impact onto the ground antennas usually involved in radioastronomy

6. CONCLUSIONS

The SPOrt payload is going to be consolidated in its definitive configuration taking into account current constrains due to:

- ISS time schedule;
- real possibility for accommodation on the EXPA together with EXPOSE (EXPOSE + SPOrt = EXPOrt). In the meanwhile the SPOrt team is putting the maximum effort to improve the SPOrt design as much as possible. Both scientific and industrial activities done up to now have shown that polarization measurements at the sensitivity level required to observe galactic foreground as well as CMB are possible, but using dedicated techniques. The SPOrt design has been optimized to do this. In our opinion there is still something better to do and the road has been opened. Future developments may deal, for example, with:
  1. small Baseline Interferometers (SBI) to allow observations at angular scales $< 1°$;
  2. lens feed horns to have either $FWHM = 2°–4°$ or more compact feed horns;
  3. more efficient active cooling;
  4. active pointing control.

But the most important result is that such measurements can be done with very simple payload configurations, also suitable for small dedicated missions. In summary SPOrt is looking also for future space opportunities that can benefit of current SPOrt activities.

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