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The Sky Polarization Observatory (SPOrt): a project to measure the diffused sky polarization from the International Space Station Alpha (ISSA)

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Abstract

The Sky Polarization Observatory (SPOrt), a project to measure the diffused sky polarization in the frequency range of 22–90 GHz from the International Space Station, is described in its current configuration. Some preliminary considerations about the general topic of polarization in radiometric observations are made, in order to introduce the importance of polarimetric measurements in the more general context of Cosmic Microwave Background observations. The International Space Station is also introduced as a quite good opportunity to address such problematics. © 1999 Elsevier Science B.V. All rights reserved.

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1. Preliminary considerations

The Cosmic Microwave Background (CMB) is considered, together with the Primordial Nucleosynthesis, the most important laboratory to study the early evolution history of the observable Universe. CMB may be addressed by measuring its three fundamental parameters:

- the absolute temperature at different wavelengths (spectrum),
- angular fluctuations at different angular scales (anisotropy),
- the polarization.

In any case, because we are leaving embedded in the Galaxy, CMB measurements have to deal with the subtraction of galactic foregrounds. For this reasons CMB observations have to be considered as indirect observations, saying that the CMB cannot be observed looking simply at the sky, even from the space. Moreover ground CMB measurements need particular instrumental configuration to limit constrains by the Earth atmosphere and only a few spectral windows may be accessed, because of the high and fluctuating atmospheric contribution. Since its discovery by Penzias and Wilson in 1965 the CMB has been widely observed and its spectrum has been determined with very high accuracy by COBE/FIRAS (Fixsen et al., 1996), with the exception of low frequencies (below 2–3 GHz), where the Galaxy severely limits the sensitivity. CMB anisotropy has been also investigated at various angular scales and the most significant detection comes from COBE/

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DMR measurements (Smoot et al., 1992). Despite of its relevance the CMB Polarization (CMBP) has not been largely observed with respect to the spectrum and the anisotropy. From the CMBP it is possible, in fact, to get information on the thermal history of the universe by putting severe constraints on the redshift of the secondary ionization. In particular, if early reionization occurred ($z = 10–50$), the large scale (few degrees) polarization is greatly enhanced whereas small scale anisotropies are significantly suppressed (Ng & Ng, 1996; Zaldarriaga & Seljiak, 1997). Moreover in case of secondary reionization (new last scattering surface) the causal horizon is larger, corresponding to larger angular scales. For a more complete discussion on theoretical aspects see Fabbri (1999). But the main reason of this quite poor investigation of CMBP must be adduced to the very low level of polarized signal to be measured. In most favorable cases, in fact, a linear polarization of a few percent of anisotropy can be expected, so leading to antenna temperatures of the order of 10^{-6} K. Such a low level cannot be measured if foregrounds are not known with the same level of accuracy (Brandt et al., 1994). Unfortunately the galactic diffuse polarized emission has not been measured extensively at frequencies higher than 1.4 GHz (Brouw & Spoelstra, 1976; Spoelstra, 1984), with the only exception of regions close to the galactic plane observed at 2.695 GHz by Junkes et al. (1987). 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. Also at these low frequencies the Galactic Polarized Background (GPB) shows significant features extending over several degrees. At frequencies below 30 GHz, in fact, the GPB is mainly synchrotron, which may be up to 75% linearly polarized (Cortiglioni & Spoelstra 1995, and references therein).

2. Some notes on the problem of polarization related to experimental techniques

1. Since CMB measurements can be done in a very large spectral range they require also very different techniques as well as different kind of detectors, which can be divided in two main categories:
   - Radiometers ($\lambda > 3$ mm) also called coherent detectors: they are polarization sensitive because they detect the electric field (E). The sensitive element in this case is a dipole-like antenna and, as it is well known, a radiometer is completely blind to a wave of the antipodal polarization state. As a general statement a radiometer fed by a dipole-like antenna will measure 1/2 of the unpolarized incident radiation plus a part, which depends on its orientation with respect to the dipole alignment, of the linearly polarized component.
   - Bolometers ($\lambda < 3$ mm) also called incoherent detectors: they are polarization insensitive because they detect power ($P \propto E^2$). The sensitive element in this case is the bolometer itself, but optics are used normally to collect photons.

Under these assumptions all CMB measurements, including spectrum and anisotropy measurements, carried on by radiometric techniques are in principle affected by polarization effects. Since galactic background has strongly anisotropic linear polarization (Brouw & Spoelstra, 1976; Spoelstra, 1984), in fact, extrapolations from total intensity maps, as well as measurements of one single component (like those done by a single channel radiometer) cannot provide correct values for galactic foreground subtraction in CMB experiments (Cortiglioni & Spoelstra, 1995). Moreover particular measurement techniques, even though carried on by double channel radiometers, are affected by spurious effects of instrumental origin that can compromise quite seriously their results. One of the major sources of systematic errors are, for example, metal reflectors used in front of feed horn antennas to redirect the beam (see Cortiglioni 1994 for a complete discussion). A quite poor understanding of such effects may imply that CMB spectrum measurements can result lower than the real one at low frequency, where the galactic contribution is stronger. In the same way residuals of galactic polarized emission may be interpreted as of extragalactic origin, so limiting de facto the sensitivity of CMB anisotropy measurements under particular experimental conditions (Cortiglioni, 1994; Cortiglioni & Spoelstra, 1995). Two possible solutions to this problem can be envisaged:

- to measure always both linear (circular) components of the incoming radiation, so that 100% of the signal is detected:

$$I = I_u + I_p = \langle E_x^2 \rangle + \langle E_y^2 \rangle = \langle E_R^2 \rangle + \langle E_L^2 \rangle,$$

- to measure the intrinsic polarization of the incoming radiation, that is to measure its Stokes parameters

$$I = \langle E_x^2 \rangle + \langle E_y^2 \rangle = \langle E_R^2 \rangle + \langle E_L^2 \rangle,$$

$$Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle = \langle 2E_R E_L \rangle \cos\delta,$$

$$U = \langle 2E_x E_y \rangle \cos\delta = \langle 2E_R E_L \rangle \sin\delta,$$

$$V = \langle 2E_x E_y \rangle \sin\delta = \langle E_R^2 \rangle - \langle E_L^2 \rangle,$$

where I_u and I_p are the unpolarized and polarized intensities respectively; E_x and E_y (E_R and E_L) are the two linear (circular) polarized components.

But that requires two different techniques based on completely different experimental approaches.

2. The instrumental polarization is the main cause of error in polarization measurements. Such a spurious effect is mainly originated in the antenna system, where the unpolarized component of the signal may produce significant polarized signal as a consequence of different causes, mainly the isolation between left and right (vertical and horizontal) propagation modes. This is particularly important when measuring the polarization of the CMB because the unpolarized component is much higher than the polarized one, their ratio being expected to be $\sim 10^6$ in the most favorable case. The high isolation between the two circular (linear) components is then the more stringent requirement in designing the antenna of a polarimeter aimed to measure extremely low levels of polarization. This spurious effect can be reduced quite well by using ‘‘switching techniques’’ together with ‘‘synchronous detection’’ (namely lock-in), but only spurious contributions generated after the switch can be affected.

3. Introducing the International Space Station

The International Space Station Alpha (ISSA) will be, after its completion in 2004, the largest space vehicle so far realized by humans. It was necessary to join experiences in space flights of both USA (NASA shuttle program) and Russia (Proton rocket) to make real this great enterprise to which contribute a total of 17 countries. Table 1 summarizes the main characteristics of the ISSA after its completion. A total of 43 flights are foreseen to complete the ISSA assembly in a very challenging schedule started last November 20th with the launch of the first element (Zarya = Sunrise) from Russia. But ISSA will be available for use also during the assembly. From late 1999, in fact, the permanent human presence will be assured onboard and from 2002 the Early opportunity phase will allow to put onboard the first lot of Externally Mounted Payloads, so that experiments can be accommodated on External Pallet Adapters (EXPA).

4. Inside the SPOrt experiment

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.

However the scenario of the CMB measurements

Table 1
Summary of main ISSA characteristics

Overall dimensions	108 m × 74 m
Mass	415 t
Electric power available on board	total 110 kW (47.5 kW for experiments)
Total available pressurized volume	1140 m^3
External surfaces available for experiments	> 50 m^2
Orbit	circular; 335–460 km height; 51°.6 inclination
Microgravity conditions	10^{-6} g in internal laboratories
Data transmissions	TDRSS downlink 43 Mbps, uplink 72 kbps

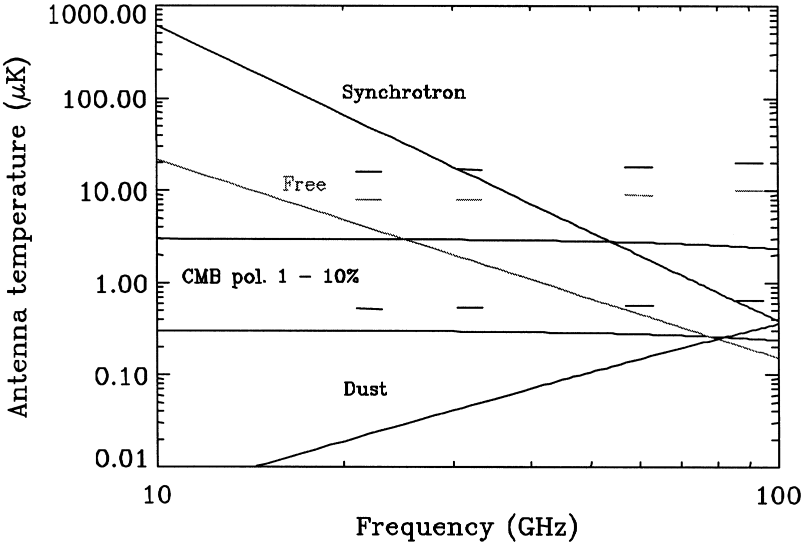

Fig. 1. Expected foreground and CMB polarized emission in the SPOrt frequency range. Horizontal ticks refer to (from top to bottom) maximum and minimum pixel sensitivity, and full sky (averaged over all the sky pixel) sensitivity. All sensitivities are calculated assuming 50% efficiency.

has changed after SPOrt-1 was proposed in 1996. Today the interest on the CMB polarization from space has grown: both MAP (a NASA space mission scheduled for 2001) and PLANCK (a ESA space program expected around year 2007) are planned for measurements of CMB anisotropies with unprecedented high degree of accuracy and they would include among their objectives the search for polarization. Both experiments, being designed to measure CMB anisotropies at small angular scales are expected to 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. The secondary ionization (reionization) of the cosmic medium is a long standing cosmological problem, to which SPOrt seems suitable to provide a solution. The SPOrt beamwidth has been chosen, in fact, to look for 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, 1995; 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 (see Fig. 1). Multifrequency full sky polarization measurements of Galactic synchrotron radio emission at high frequencies (where Faraday rotation and depolarization is negligible) to be made by SPOrt will allow to study the radio spectrum of total Galactic synchrotron radio emission (the knowledge of this spectrum helps one to separate three 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. But as it is well known the ISSA is very different from a free-flyer. It must be considered rather as a facility which can accommodate a variety of experiments in different fields from outside the Earth atmosphere. The 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 experiment's 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.

Major differences between SPOrt-1 and the current SPOrt configuration (Cortiglioni et al., 1999) regard:

- Frequency coverage.
- Number of channels.
- Front-end Low Noise Amplifiers (LNA).
- Cooling.
- Antenna beam width (FWHM).
- Pointing.

1. *Frequency coverage*: the 10–30 GHz range has been originally proposed mainly based on the need of new and full sky measurements of the linear polarization of the diffuse galactic emission (GPB). Also the availability of commercial components was taken into account.

   But the scenario changed very rapidly and the opportunity to attempt measurements of the CMB polarization convinced the SPOrt team to extend the frequency coverage up to 90 GHz. On the other side the room available on the EXPA does not allow the 10 GHz feed accommodation because of its physical dimensions.
2. *The number of channels* has been optimized to four within the 20–90 GHz range, to allow a recognition of the various contributions 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. *Good Low Noise Amplifiers (LNA)* at 10–30 GHz were of common use in radioastronomy when SPOrt-1 was proposed. However the current SPOrt design requires more critical LNAs. LNAs for space applications, in fact, are not commercially available at frequencies higher than ~40 GHz and those available have quite poor noise figures. TRW (USA) should be in charge of LNAs supply to SPOrt.
4. *The cooling* of the SPOrt-1 front-end was supposed to be passive. Further investigations on the ISSA environment showed however that passive cooling is insufficient to let LNAs operate under the best conditions. An active cooling system has been implemented in the current SPOrt design, which is expected to keep LNAs at temperatures ≤ 80.
5. *The SPOrt-1 antennas* had FWHM = 4°–6° (2° with lens horns), but the long time necessary to develop them and uncertainties about the noise produced by lenses drove to larger beam design. It has been decided to give maximum priority to realize feed horns with extremely good performances in terms of sidelobes and cross-polarization. The current value of FWHM = 7° looks reasonable for both manufacturing and scientific objectives.
6. *SPOrt-1* included a Coarse Pointing Device (CPD) provided by ESA. Subsequently however this device was eliminated by ESA to leave room for other payloads, which have to be accommodated inside the EXPA. SPOrt does not have therefore any pointing device and it will observe in sky scanning mode from a fixed position (in the zenith direction). More than 80% (663 pixels of 7°) of the sky may be observed with different integration time (Fig. 2).

5. 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 (a few μK per pixel 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.

SPOrt is now a set of four identical correlation receivers whose central frequencies are: 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 Fig. 3.

The horn plus the iris polarizer and the Orthomode

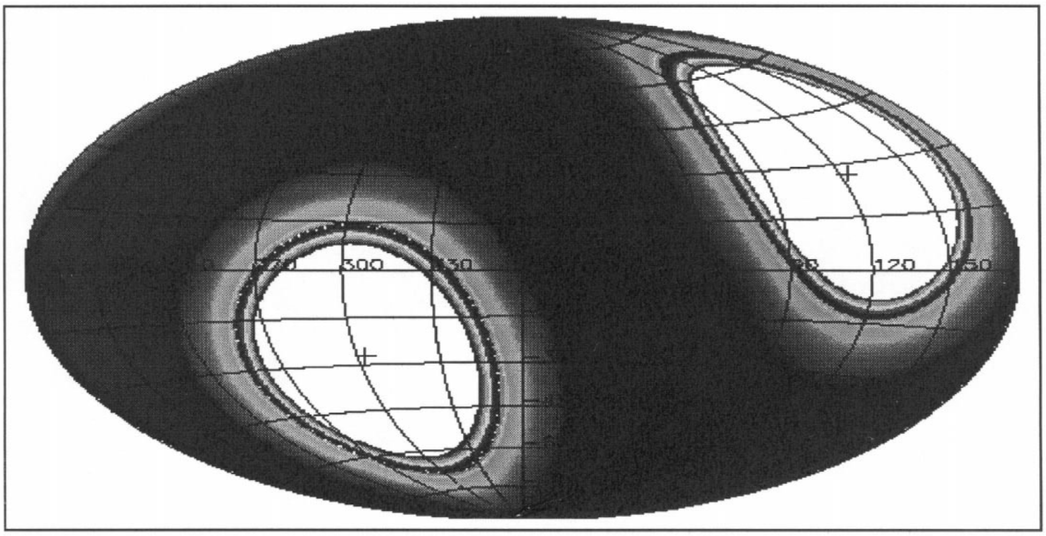

Fig. 2. The sky that can be seen from the ISSA observing towards the zenith (82%). Grey scale represents the integration time (regions around Celestial Poles cannot be observed).

Transducer (OMT) splits the incoming radiation (unpolarized plus polarized) in two components circularly polarized in opposite directions. These signals are fed in two identical chains where LNAs amplify signals to provide inputs to the correlation unit. This unit, a combination of a passive Hybrid Phase Discriminator (HPD), square law detectors, differential amplifiers and a time integrator, averages out all signals providing two outputs proportional to the Stokes parameters U and Q of the radiation.

Fig. 4 shows a typical configuration of SPOrt HPDs. To reject spurious contributions due to cross-polarization in the correlation unit (HPD), a ‘‘(0°–180°) phase switching technique’’ has been adopted together with a phase sensitive detector (namely lock-in) which also eliminate both off-sets and the low frequency $1/f$ noise. The overall effect can be summarized as:

Phase switch in 0° position	Phase switch in 180° position
$V_1 = k[(A^2 + B^2) + 2AB\cos\delta]$	$V_1 = k[(A^2 + B^2) - 2AB\cos\delta]$
$V_2 = k[(A^2 + B^2) - 2AB\cos\delta]$	$V_2 = k[(A^2 + B^2) + 2AB\cos\delta]$
$V_3 = k[(A^2 + B^2) + 2AB\sin\delta]$	$V_3 = k[(A^2 + B^2) - 2AB\sin\delta]$
$V_4 = k[(A^2 + B^2) - 2AB\sin\delta]$	$V_4 = k[(A^2 + B^2) + 2AB\sin\delta]$
$V_1 - V_2 = kAB\cos\delta \propto Q + \text{Offset}$	$V_1 - V_2 = -kAB\cos\delta \propto -Q + \text{Offset}$
$V_3 - V_4 = kAB\sin\delta \propto U + \text{Offset}$	$V_3 - V_4 = -kAB\sin\delta \propto -U + \text{Offset}$

where A and B represent Left Hand Circular and Right Hand Circular components; δ is the phase delay between A and B; $V_i = |C_i|^2$ (see Fig. 4). Offsets will disappear after phase sensitive detection $[\Delta V_{(0°)} - \Delta V_{(180°)}]$ as well as all terms with the same sign. The sensitivity (minimum detectable signal) for a correlation radio-polarimeter is given by (see for instance Krauss, 1986) $\Delta T = T_{\text{sys}} \sqrt{2(1+\beta)/t_{\text{int}}\Delta f}$, where T_{sys} is the (total) system noise temperature, t_{int} is the integration time, Δf is the RF bandwidth, and 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 Fig. 1 and Table 2). This is done through off-line analysis. Very high system stability as well as accurate pointing recognition are required to allow superposition (a posteriori) of data arriving from the same spot on the sky observing at different times.

Continuum system monitoring and internal calibration are obtained by injection, before the iris polarizer and the OMT, of a known noise signal. Table 2 reports the expected sensitivity for each SPOrt channel.

6. Conclusions

The SPOrt experiment is currently in a so-called

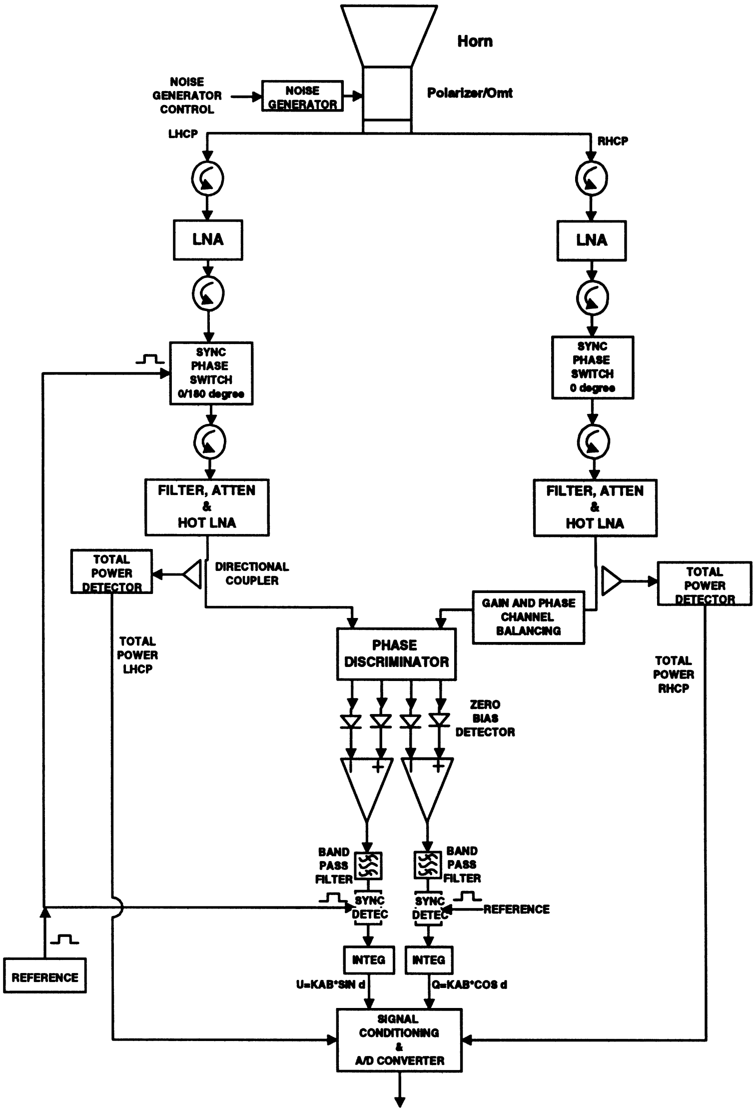

Fig. 3. Schematic block diagram of SPOrt's correlation polarimeters.

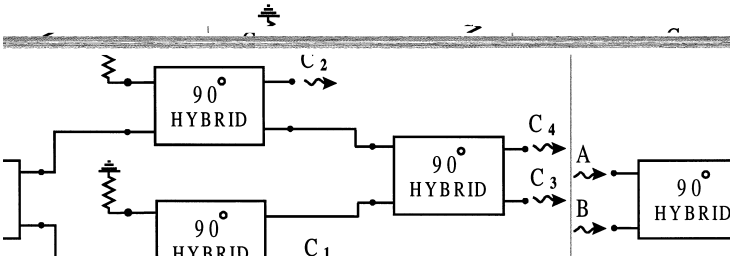

Fig. 4. A typical configuration of SPOrt's Hybrid Phase Discriminators.

Table 2
For each SPOrt channel are reported the overall system temperature, the instantaneous sensitivity, the long term expected sensitivity (average) and the full sky sensitivity (averaged over all pixels)

Frequency (GHz)	T_{sys} (K)	ΔT_{RMS} (mK $\mathrm{s}^{-1/2}$)	Average RMS/pixel (μK)	Full sky sensitivity (μK)
22	65	2 (+0.3)	13.4	0.52
32	82	2 (+0.3)	13.8	0.54
60	119	2.2 (+0.2)	14.7	0.57
90	167	2.5 (+0.2)	16.8	0.65

A-B bridging phase aimed to consolidate the payload configuration on the EXPA together with another payload named EXPOSE. The combined payload is named EXPOrt and will take a full EXPA (Fig. 5). After completion of this phase, by the end of 1998, phase B will take place in order to fit the ISSA schedule, which foresees the delivery of the SPOrt payload to ESA and NASA by the end of 2001. The first flight opportunity will be in early 2002, during flight Shuttle UF-4.

Acknowledgements

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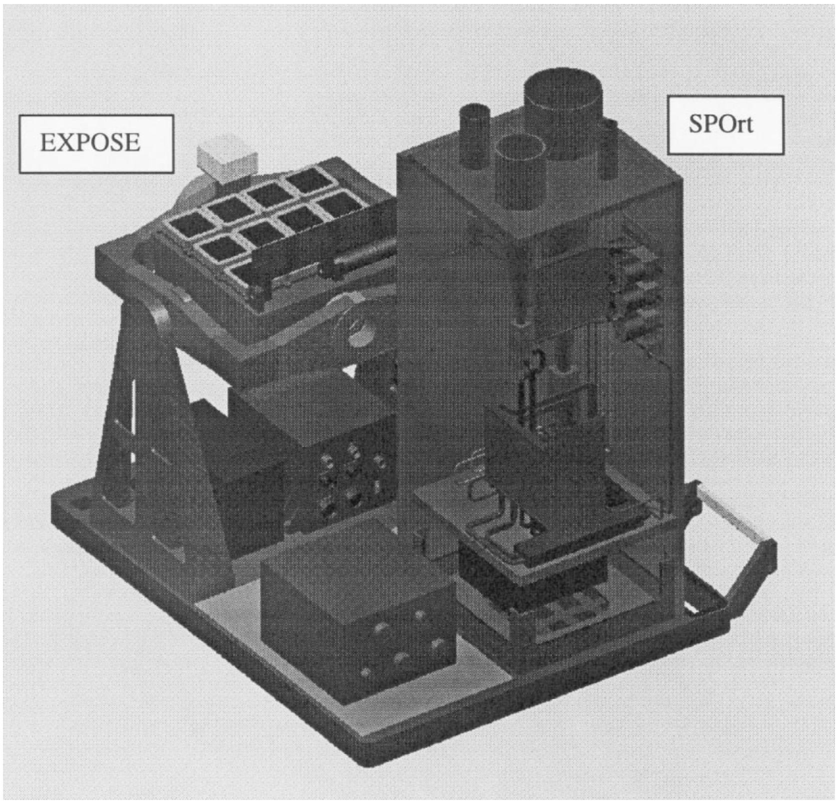

Fig. 5. Layout of the EXPOrt Pallet Adapter.

Space Agency for supporting A-B bridging phase industrial activities under EPI contract.

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