BaR-SPOrt: AN EXPERIMENT TO MEASURE THE LINEARLY POLARIZED SKY EMISSION FROM BOTH THE COSMIC MICROWAVE BACKGROUND AND FOREGROUNDS

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Abstract

The BaR-SPOrt experiment is aimed at measuring the polarization of the microwave sky at 32 and 90 GHz with sub-degree angular resolution. In this spectral and angular window it is possible to detect the polarization of the cosmic microwave background, which is one of the most ambitious goals of the today astrophysics. The experiment has been designed to fly onboard a Long Duration Balloon to be launched from polar regions, where it is possible to observe low foreground emission sky patches situated at high galactic latitudes.

1. INTRODUCTION

Despite the huge number of experiments dedicated to investigate the Cosmic Microwave Background (CMB) since its discovery in 1965, CMB still represents one of the most challenging research fields for modern astrophysics. Its (black body) spectrum has been measured with high accuracy by COBE-FIRAS [1] in a wide range of wavelengths and its anisotropy has also been characterized by measuring its angular power spectrum from degree to arcminute angular scales [2][3][4][5]. These studies have told us that the universe is topologically flat and that it experienced a period of exponential growth, the so called inflation, about 10^{-34} seconds after the Big Bang [6][7][8]. A renewed interest in further CMB investigations has been stimulated by the need both to probe the inflationary epoch and to break the degeneracy of some cosmological parameters, which is not possible with anisotropy data alone [9][10]. Measuring the polarization of the CMB and its angular power spectrum can efficiently do this. The first-year data of the WMAP satellite [5] have allowed us to obtain the temperature-polarization (TE) cross power spectrum [11], from which the redshift (z_r=20 +10/-9) at which the universe was reionized, as well as the optical depth (τ=0.17+/-0.04) of the medium, have been deduced. However, WMAP did not provide any

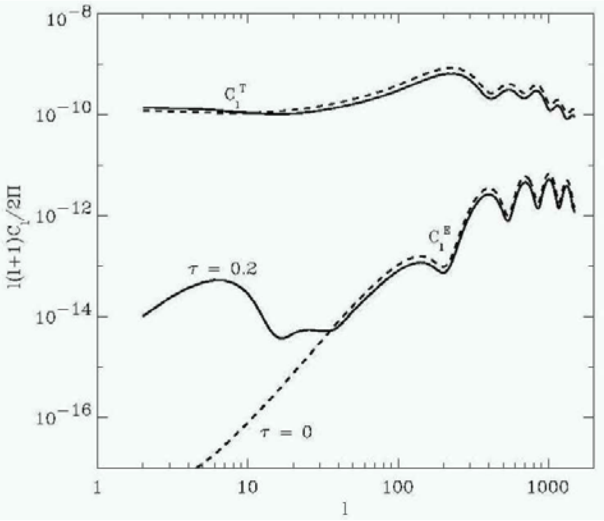

Figure 1. The CMB anisotropy (upper) and polarization (lower) angular power spectra.

polarization map yet. The CMB Polarization (CMBP) signal, in fact, is about one order of magnitude lower than the anisotropy one, its detection representing a real challenge for experimenters. Nevertheless, a first detection of the CMBP signal has been claimed by the DASI team [12], confirming that the scientific goal is achievable even though a *clean measurement* has still to be done. A clean measurement of CMBP at sub-degree angular scale is exactly the goal of the BaR-SPOrt (Balloon-borne Radiometers for Sky Polarization Observations) experiment, which is sharing the basic technology of the SPOrt program [13] [14] [15].

2. THE ASTROPHYSICAL SCENARIO

Even though the large angular scales represent the true mine of information for obtaining cosmological parameters, their investigation can be done only from space. Space experiments, in fact, can benefit of the unique possibility to have long integration times in really quiet and stable conditions, which are the basic requirements for all sky surveys. Figure 1 shows how much sensitive is the E-mode angular power spectrum of the CMBP, at larger angular scales, to the reionization, with respect to the anisotropy one. But the most exciting task for future CMBP experiments is to measure the B-mode spectrum, which is directly related to the tensor-to-scalar perturbations ratio T/S (Figure 2). Its value is in turn related to the energy of the universe at the inflation time [16][17], thus the B-mode allows the estimate of the energy at which the inflation occurred. Unfortunately, the detection of the B-mode shall require a sensitivity still higher than that allowed by current technology. Current experiments have also the task of testing new instrumentation for future B-mode investigations.

BaR-SPOrt is aimed at investigating the E-mode power spectrum at sub-degree angular scales, where the coherent primordial fluctuations predicted by inflation leave fingerprints like a well defined Doppler peak pattern, whose maxima correspond to minima in the anisotropy spectrum and vice versa (Fig. 1).

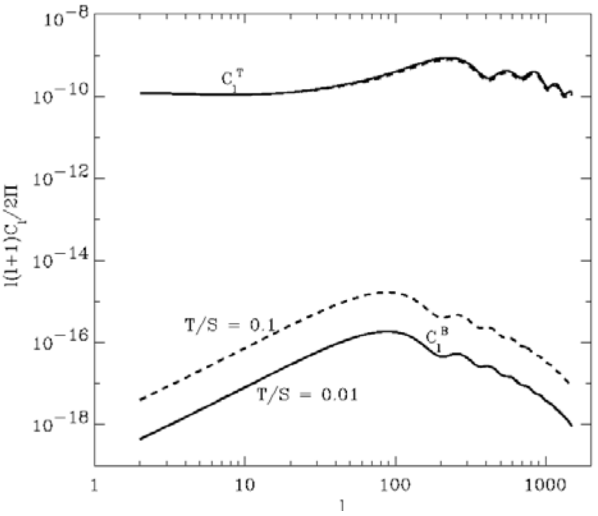

Figure 2. The B-mode angular power spectrum of CMBP

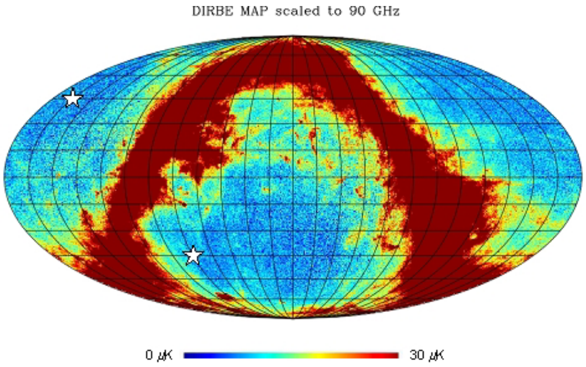

Figure 3. The COBE-DIRBE map scaled at 90 GHz. The two identified sky patches are also shown.

Major problems for *genuine* CMBP detections are represented by:

- Spurious (instrumental) polarization
- Foreground contamination (Galactic synchrotron, dust)

The spurious polarization is generated by unwanted contributions from unpolarized radiation, producing offsets whose fluctuations degrade the ideal sensitivity by preventing long integration times. The limits due to instrumental polarization in CMB experiments have been deeply discussed in [18], where the advantages of correlation radiometers have been extensively analyzed.

The case of Galactic foreground emission, for which no polarization data exist at frequency higher than 2.7 GHz, has been also faced basically in two different ways:

- By constructing a template for the Galactic polarized synchrotron emission based on available radio and optical data [19]
- By making deeper observations of some sky patches expected to show low emission [20].

The result is that at least two low emission sky patches (Figure 3) have been identified in both the Southern and the Northern hemisphere, where the expected mean polarized signal (P_{rms}) could allow E-mode measurements even at 30 GHz. The 90 GHz spectral window looks more promising for both E and B-mode with no significant synchrotron contamination [20].

3. THE GOAL AND THE OBSERVING STRATEGY

The main goal of the BaR-SPOrt experiment is the measurement and characterization of the CMBP on sub-degree angular scales. Its resolution, 0°.2 for the 90

GHz channel, allows measurements where the CMBP spectrum has its peak emission. The 9 receivers configuration (see section 4.1) will lead to detect the signal on a nearly 6°x6° area of the sky with enough pixel sensitivity to determine the E-mode power spectrum close to the Cosmic Variance limit: a better sensitivity would allow a better CMBP description only on a larger sky patch. For comparison, a similar sensitivity can be reached from ground in about six months of useful integration on a 20°x20° patch.

The observing strategy is strictly dependent on the data reduction algorithm. To avoid the 1/f noise from gain fluctuations, a signal modulation together with proper *destriping* algorithms must be applied. The *destriping* technique for BaR-SPOrt is an easy variant of that already developed for SPOrt [21]. It gives the best result when the target region is scanned along stripes crossing each other. This is realized by observing the sky with horizontal scans covering all the interested area. The different inclination of the patch with respect to the horizon given by its daily path in the sky provides the proper stripe-crossing. The BaR-SPOrt receiver long-term stability (of the order of several hours) allows scan periods compatible with those achievable in Balloon-Borne experiments (~1 minute), providing a proper signal modulation.

4. THE PAYLOAD

4.1 The receivers

The BaR-SPOrt experiment has been designed to operate as a payload for stratospheric balloon in two steps:

- 1st: with a 30 GHz channel alone
- 2nd: with an array of 90 GHz receivers

Table 1. BaR-SPOrt expected sensitivities for a two weeks flight on 100 pixels (6°x6°) at 32 GHz and on 900 pixels (6°x6°) at 90 GHz: σ1s and σpx are the instantaneous and final sensitivity per pixel, respectively.

f (GHz)	BW	HPBW	σ_{1s} [mKs$^{1/2}$]	σ_{px} (μK)
32	10%	≈0°.4	0.5	4.5
90	20%	≈0°.2	0.5	4.5

Both of them are based on the SPOrt receiver architecture, which makes use of correlation receivers whose main characteristics are summarized in Table 1.

The BaR-SPOrt receiver design (Figure 4) is able to provide the Q and U Stokes parameters as a result of a direct analog correlation of the two circular components (A, B) of the electric field, performed onboard over a bandwidth up to 20%.

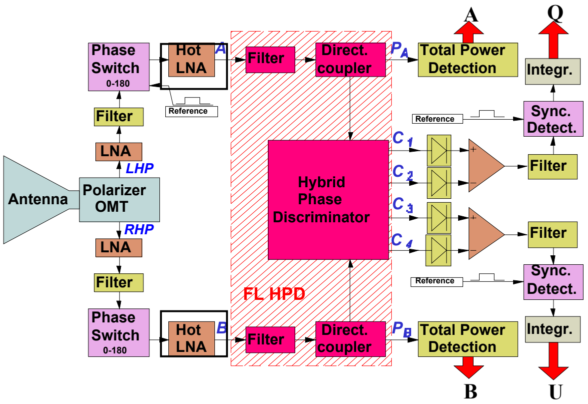

Figure 4. The SPOrt receiver architecture

In principle such a design is the best, in term of systematics contamination, to achieve the goal of measuring the CMBP signal, but the residual systematics must be taken lower than the expected CMBP level (only $\sim 10^{-6}$ of the total CMB signal). In the light of this, the analysis performed by the SPOrt team has highlighted the following basic requirements:

- Direct amplification architecture: down conversion may introduce additional phase errors
- On axis low cross-polarization optics
- Correlation Unit (CU) providing >50 dB of total unpolarized component rejection; it is based on a Hybrid Phase Discriminator (HPD), able to reject the unpolarized component at a level better than 30 dB, plus a phase modulation system (lock-in)
- Orthomode Transducers (OMT) with isolation >60 db to minimize the spurious correlation
- Low Noise Amplifiers (LNA) operating at cryogenic temperature (<80 K) with stability ≤0.1 K
- New design Onboard Calibration System (OCS) to inject reference polarized signals able to give a complete characterization of the polarimeter.

In particular, since *state of the art* commercial components cannot match the fundamental requirements, it has been necessary to design and build some really special devices, which represent really a

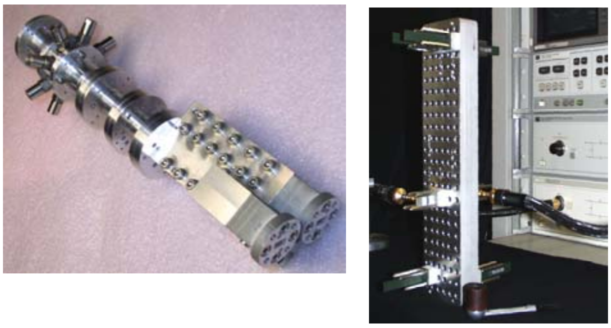

Figure 5. Part of the 32 GHz antenna system. From top-left to bottom-right are: the polarizer, the marker injection system and the orthomode transducer.

Figure 6. The optics and the cryostat

new frontier for such waveguide components (Fig. 5):

- Orthomode Transducers (OMT) [22]
- Polarizers [23]
- Marker Injection System (MIS) [24]
- Hybrid Phase Discriminators (HPD) [25]

4.2 The BaR-SPOrt optics

Since off-axis optics produce intrinsically high spurious polarization, BaR-SPOrt has a highly symmetric double Cassegrain optics of Ø=180 cm, providing HPBW≈0°.4 and 0°.2 at 32 and 90 GHz, respectively. Both the primary and the secondary mirrors are realized to match mechanical and thermal specifications for use in stratospheric balloon experiments.

4.3 The BaR-SPOrt cooling system

A cryostat is necessary to provide a cold and stable environment for the receiver and the electronics. It has a cold part kept at a temperature <80K by means of a mechanical cryocooler (supplying 6W @ 77K), housing the front end. A temperature stability <0.1K is guaranteed by a careful thermal design and by a closed loop which is controlled by the cooler electronics.

4.4 The BaR-SPOrt Gondola and Pointing System

The pointing system is a key part of any balloon-borne experiment. It has to achieve the attitude stabilization required by the scientific instrumentation during the flight as well as guarantee the post flight pointing reconstruction. Generally speaking, the Attitude Control System (ACS) includes two main parts: the azimuth control and the elevation control. Since BaR-SPOrt requires a pointing accuracy in the order of 1 arc-minute, a particular attention has to be dedicated to the choice of the absolute sensors. Both the need of accurate pointing reconstruction and the need of redundancy typical of LDB suggest the use of multiple sensors, like *magnetometer* (coarse or sector sensor), *sun* and *star tracker* as well as inertial sensor (*gyroscope*) in order to describe the *pendulum* motion of the flight chain. In particular, the magnetometer, besides being tuned for the actual expected latitude of the balloon flight trajectory, needs to be corrected for the magnetic declination error. This is done by the flight program, which includes a world magnetic model (WMM) and receives the output of a GPS receiver. The ACS has a mechanical part (*pivot*) and an electronic part [26][27][28]. The first one is located at the balloon-platform interconnecting point and is aimed both at pointing the payload towards scientific targets and at counterbalancing the torque coming from the random rotation of the balloon. This last action is necessary to keep (permanently) active the correcting torque of the control loop. The elevation movement needs an independent motor controlled by a 16 bit optical absolute encoder. The *pivot* houses two motors

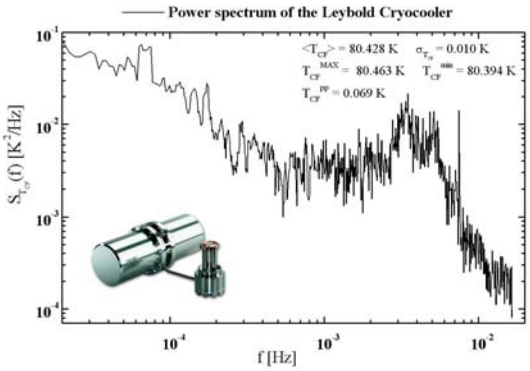

Figure 7. Power spectrum of the cooler obtained in a 6 days test run

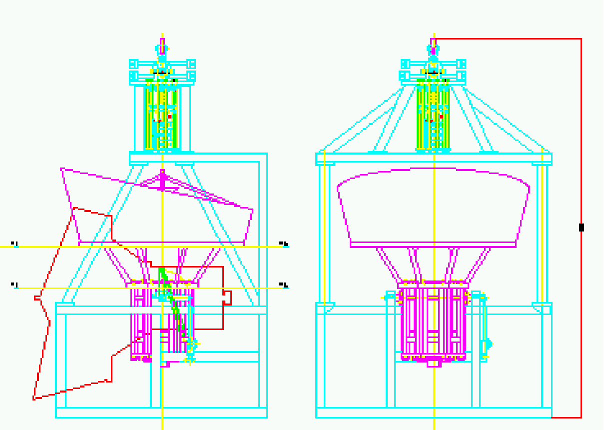

Figure 8. The BaR-SPOrt Gondola

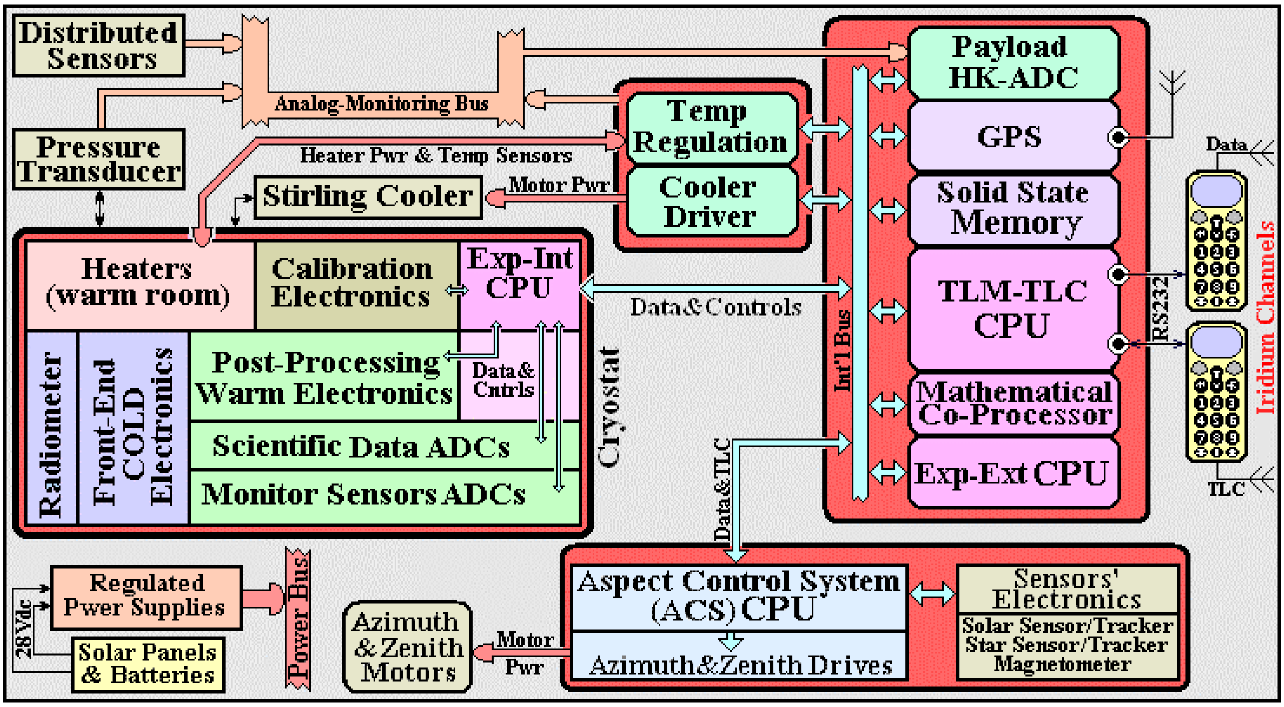

Figure 9. Schematic functional diagram of the Service Electronics

(Kollmorgen QT6205-d with a torque sensitivity kt=1.4 Nw.m/A). All the mechanical parts, for instance the *pivot* and the *gondola*, are designed according to the safety requirements (10g vertical and 5g at 45 degrees) of NASA-NSBF, recently adopted also by the Italian balloon base of Milo (Trapani-Sicilia). The actual pivot design is able to drive payloads up to 2500 Kg of total weight.

The ACS electronics of BaR-SPOrt is a *full digital system* characterized by a great versatility. It allows an easy management (via software) of any weight and/or inertia moment combinations as well as every measurement strategy control. Each of the mentioned sensors (*sun*/*star-tracker* and *gyroscope*) has its own CPU in order to dedicate the main ACS CPU (a robust AMPRO 386 *SXI*) to the flight strategy.

4.5 The Service Electronics

The BaR-SPOrt in-flight configuration is schematically shown in the functional block diagram of Figure 9. With the exception of the Cryostat and the Detection apparatus (Radiometer with the associated equipments), which have been specifically designed for this experiment, the guide (basic) criterium followed in its design has been to develop a system able to match the requirements of a general-purpose scientific balloon-borne instrumentation. This has led to an implementation (Fig. 9) able to reliably process both analog and digital information under the control of distributed intelligence, i.e. several CPUs' allocated in the subsystems rather than a unique central CPU overheading the whole experiment. As a consequence, any subsystem can be more easily debugged and, at the same time, controlled during setup and test phases. Furthermore, using active redundancy for every CPU and other devices whose wrong working conditions could compromise the aim of the experiment, considerably reduces the probability of faulty operations. The communication protocols between the distributed CPUs' are standard so that both data and controls are easily exchanged between the subsystems. Scientific and housekeeping data are collected by the TLM-TLC CPU, which manages both the telemetry data formatting and the remote commanding. The auxiliary Exp-Ext CPU and Math Co-Processor provide control of the data traffic among different radiometer equipments and the calculations required to update the astronomical (pointing) coordinates, respectively. Inside the Cryostat (both cold and warm rooms operating at a residual pressure of $\sim 10^{-8}$ bar) data and controls are locally managed by the Int-CPU, which also handles all the functions required to extract scientific and housekeeping data including the Analog-to-Digital Conversions (ADCs') as well as the calibration facilities. Other specific tasks (Vacuum Pump drive, thermal regulation of the warm room, Cryostat pressure monitoring, payload parameters monitoring) are interfaced by dedicated subsystems managed by the Exp-Ext CPU.

The absolute timing reference for the experiment is retrieved by the GPS, which is actively redundant. The GPS, whose data are shared with the Attitude Control System (ACS), also supplies the Longitude and Latitude data necessary to update (Math Co-Processor) in quasi-real time the astronomical coordinates of the sky area to be scanned by the ACS. The attitude sensors/trackers, connected to the ACS, continuously feed the ACS-CPU with the error between the actual pointing position with respect to the programmed sky target: this is translated into feedback drive excitations to the motors until the error is reduced below the system resolution (few arcsec). Since observations at fixed Zenith angles are normally performed by simply issuing scanning at an Azimuth constant speed $\pm\ \omega$ (deg/s), the possibility to insert meaningful scientific data into the Telemetry (TLM) format strongly depends on the ratio ω/BR, where BR is the TLM Bit Rate (BR, kbps). Flying at high latitudes (long duration balloon flights around the Arctic) prevents from using normal TLM radio links since it could produce heavy loss of data reception at the ground station. Incidentally, it should be emphasized that BaR-SPOrt will keep full data storage in the Solid State Memory (Fig. 9).

4.6 The Telemetry/Telecommand system

Since a basic requirement of a balloon experiment resides in the possibility to have a continuous data visibility during the flight so that to possibly interact with the on-board systems by issuing remote commanding actions (TLCs), for BaRSPOrt it was decided to attain full data coverage by lowering the scientific data sampling requirements, without degrading the scientific objectives. This requirement has been achieved thanks to the really good receiver stability, which allows scan periods in the order of several minutes. Consequently, both the sampling and the data transfer rate became compatible with commercial satellite phone links. The only possibility for an “around arctic” balloon flight was to use commercial phone channels provided by the Iridium Satellite System, which also permits data transmission at maximum speed of 2.4 kbps. This dictates to lower the ACS Azimuth speed down to $\omega \approx 5$ arcmin/s. Furthermore, to be able to also perform the X-mitting function of TLCs’ to the experiment instrumentation, a second Iridium channel has been reserved to the remote commanding. The use of a couple of Iridium channels permits to have a remote control of the TLM/TLC links giving a sort of redundancy in case of faulty operations during the flight.

Any function performed by the experiment subsystems, which have been previously described, is coded and stored in the on-board Software. In general, the experiment should operate in automatic mode with on-board pre-stored routines, but any parameter or routine can be remotely varied by issuing TLCs from the ground equipment.

5. THE BAR-SPORT PROGRAM SCHEDULE

BaR-SPOrt can reach its goal to detect the CMBP signal with at least 2 weeks of integration time. That is possible only through Long Duration Balloon (LDB) Flights, for which the experiment has been designed. Such flights are possible only from Antarctic and Arctic sites, where the stratospheric wind circulation allows the balloons to go along an almost circular trajectory for weeks [29][30][31]. The Italian Space Agency, which supports the BaR-SPOrt experiment, has planned a *pathfinder* campaign to test LDB feasibility from Svalbard (Norway) in Summer 2003 [32].

After integration and preliminary tests, to be completed by Spring 2004, the experiment shall be used for a ground test observational campaign from the Arctic base of CNR, located at Ny-Alesund (Svalbard). The payload should be ready for a first launch opportunity starting from Summer 2004.

AKNOWLEDGEMENTS

The BaR-SPOrt experiment is supported by the Italian Space Agency (ASI) and by the Programma Nazionale di Ricerche in Antartide (PNRA). The authors wish to thank the Consiglio Nazionale delle Ricerche for the valuable support to operations at Svalbard.

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