COBRAS/SAMBA
The definitive Cosmic Microwave Background anisotropy mission

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Abstract

The primary objective of the COBRAS/SAMBA mission is to image the temperature anisotropies of the Cosmic Microwave Background (CMB) radiation field, to a sensitivity level of $\Delta T/T{\sim}2{\times}10^{-6}$ (T$\sim$ 2.726 K) and with an angular resolution of 10 arcminutes. To achieve this objective, it will survey the whole sky in nine frequency bands ranging between 30 GHz and 900 GHz, with an angular resolution varying between 30 and 4.5 arcminutes. The spectral information will be used to subtract from the observed signal the emission due to our own and other galaxies, and recover the primordial (CMB) information. The maps of the CMB fluctuations will be used to test models of the early Universe, determine fundamental cosmological parameters to a precision of a few percent, investigate the initial conditions for the formation of structure, and constrain the nature of the dark matter. In addition, detection of the Sunyaev-Zeldovich effect in thousands of rich clusters of galaxies will allow the study of their properties and evolution. Finally, catalogues of extragalactic sources and maps of our own Galaxy will yield a wide spectrum of astrophysical science.

1 Introduction

COBRAS/SAMBA is a mission devoted to the study of the temperature fluctuations - often called anisotropies - of the Cosmic Microwave Background radiation field (CMB). The scientific objectives and capabilities of COBRAS/SAMBA are presented elsewhere in these proceedings, and thus we here concentrate on a brief description of its technical characteristics. For completeness' sake a summary of the scientific areas addressed by COBRAS/SAMBA is shown in Table 1. A general overview of the technical description is shown in Table 2.

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[1] This article is based on the results of ESA's COBRAS/SAMBA Phase A Study, which are presented in more detail in the Phase A Report, ESA D/SCI(96)3. The Science Team leading the Study included M. Bersanelli, M. Griffin, J.M. Lamarre, N. Mandolesi, H.U. Norgaard-Nielsen, O. Pace (Study Manager), J. Polny, J.L. Puget, J. Tauber (Study Scientist), and S. Volontè. The industrial part of the study was carried out by a team of engineers from Matra Marconi Space (Toulouse), led by C. Koeck. Technical support was also provided by specialists from the ESA Technical Directorate (ESTEC) and the Directorate of Operations (ESOC). Many other people contributed to various scientific and technical aspects of the Study; their names are too numerous to list here, but we wish at least to acknowledge the substantial contributions by F. Bouchet and G. Efstathiou.

But first, a word of history: in response to ESA's call for M3 proposals, two projects were presented devoted to the study of the anisotropies of the CMB. COBRAS (Cosmic Background Radiation Anisotropy Satellite) and SAMBA (Satellite for Measurement of Background Anisotropies) were both conceived as 1 meter-class telescopes, each carrying broad-band detection systems at four different frequencies, in the case of COBRAS in the range 30 to 130 GHz, and in that of SAMBA 140 to 800 GHz. COBRAS and SAMBA together span a range of frequencies which, due to technical limitations, would be impossible to achieve for each of them alone. Early on in the Assessment phase it was recognized that to meet its scientific objectives COBRAS/SAMBA would have to provide the widest possible frequency range. Therefore, the two original (COBRAS and SAMBA) instruments were merged into a single payload. Since then, the combined project has been studied at the Assessment and Phase A levels by ESA, and shown both to be capable of meeting its scientific objectives and of fitting within the (financial and technical) constraints of a medium-sized mission.

Table 1. Scientific areas addressed by COBRAS/SAMBA

Component	**Area**	**Highlights**
CMB	Cosmology & origin of structure	• Initial conditions for structure evolution • Constraints on particle physics at energies $>10^{15}$ GeV: – Origin of primordial fluctuations – Testing and characterizing inflation – Testing and characterizing topological defects • Constraints on the nature and amount of dark matter • Determination of fundamental parameters: – Ω_0, H_0, Λ to 1% – Ω_b, Q_{rms}, n_s to a few %
SZ	Cosmology & structure evolution	• Measurement of y in $>10^4$ clusters • Estimate of H_0 from y and X-ray measurements • Cosmological evolution of clusters • Bulk velocities (scales >300 Mpc) out to $z \simeq 1$ with $\Delta v \simeq 50$ km/s
Extragalactic sources	Cosmology & structure formation	• Source catalogues of – IR and radio galaxies – AGNs, QSOs, blazars – inverted-spectrum radio sources • Far-infrared background fluctuations • Evolution of galaxy counts
Dust emission	Galactic studies	• Dust properties • Cloud and cirrus morphology • Systematic search for cold cores
Free-free and synchrotron		• Determination of spectral indices • Cosmic ray distribution • Magnetic field mapping

2 Scientific Requirements

The ambitious scientific objectives of COBRAS/SAMBA can only be met by fulfilling a number of stringent experimental specifications:

- Very high sensitivity ($\Delta T/T \sim 10^{-6}$), requiring the use of state-of-the-art detection techniques.
- The ability to probe all angular scales between ~10 arcminutes and 180° . The 10' angular resolutions sets the size of the effective aperture of the payload telescope to be of order 1 meter in diameter.
- The ability to survey a large fraction of the sky, to improve the statistical properties of the data set.
- Coverage of a large range of frequencies, to monitor and separate the emission from all potential foreground sources. By simulation the required frequency range has been specified as ~30-800 GHz, requiring two technologically different types of detectors: tuned radio receivers at low frequencies and bolometers at high frequencies.

In addition to these basic requirements, the payload must be designed with the goal of reducing its sensitivity to systematic effects, mainly those due to straylight and thermal modulation.

The COBRAS/SAMBA mission is designed to comply with all of these requirements. In fact, our best current knowledge indicates that at the 10' angular scale, residual foreground fluctuations will limit any attempt to exceed the goal sensitivity levels of COBRAS/SAMBA , thus justifying its description as a "definitive" experiment.

Table 2. **COBRAS/SAMBA Mission Summary**

PAYLOAD									
Telescope	1.5 m Diam. Gregorian; shared focal plane; system emissivity 1% Viewing direction offset 70° from spin axis.								
Center Frequency (GHz)	31.5	53	90	125	143	217	353	545	857
Detector Technology	HEMT radio receiver arrays				Bolometer arrays				
Detector Temperature	~100 K				0.1-0.15 K				
Cooling Requirements	Passive				Cryocooler + Dilution system				
Number of Detectors	4	14	26	12	8	12	12	12	12
Angular Resolution (arcmin)	30	18	12	12	10.3	7.1	4.4	4.4	4.4
Optical Transmission	1	1	1	1	0.3	0.3	0.3	0.3	0.3
Bandwidth $(\frac{\Delta\nu}{\nu})$	0.15	0.15	0.15	0.15	0.37	0.37	0.37	0.37	0.37
$\frac{\Delta T}{T}$ Sensitivity per res. element (14 months, 1σ, 10^{-6} units)	7.8	7.5	14.4	35.4	1.2	2.0	12.1	76.6	4166

SPACECRAFT	
Launcher	Ariane 5 (Dual- or triple-launch Configuration, SILMA Fairing)
Orbit	Lissajous around Sun-Earth L2 point
Stabilization	Spinner at 1 rpm
Pointing (2σ)	$2\overset{\prime}{.}5$ a posteriori
Lifetime	1.5 yrs baseline, 5 yrs extended
Operations	10-11 hr per day contact; one ground station
Total mass	1523 kg
Total power	693 W

3 Model Payload Architecture

There are three basic payload components: (1) a telescope and baffling system, providing the angular resolution and rejection of straylight; (2) the Low Frequency Instrument (or LFI) – arrays of tuned radio receivers, based on HEMT amplifier technology, and covering the frequency range ~30 - 135 GHz; and (3) the High Frequency Instrument (or HFI) – arrays of bolometers covering the frequency range ~116 - 900 GHz. The LFI and HFI are both placed in the focal plane formed by the telescope, and share the focal area equally. This arrangement maximizes the optical throughput to each instrument, while keeping off-axis aberrations to an acceptable level.

The temperature requirements of the two types of detector are very different, the HEMTs giving adequate performance at 100 K (achievable by passive cooling), while the bolometers must operate at temperatures between 0.1 and 0.15 K to achieve the required performance. Thus, while the LFI will simply consist of an array of corrugated horns feeding miniaturized receivers, the bolometers must be placed inside a "cold box" consisting of a series of nested radiation shields, and cooled by an open-cycle dilution refrigerator coupled to a mechanical 4 K cooler.

A schematic overview of the arrangement of the payload is shown in Figure 1(a).

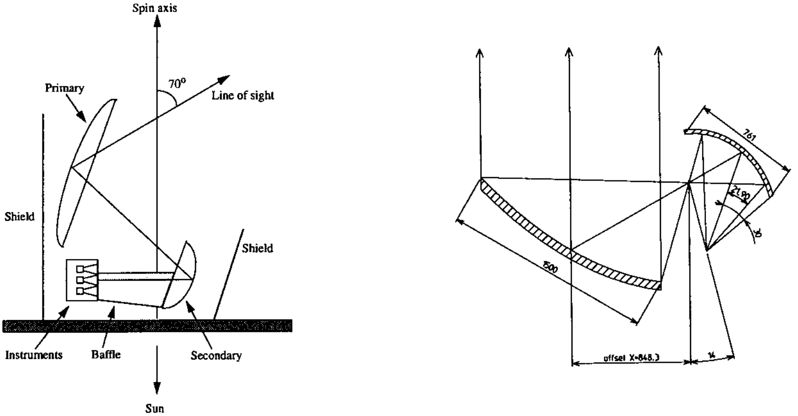

Figure 1: (Left) A sketch of the geometric architecture of the payload. (Right) A sketch of the configuration of the mirrors. Linear dimensions are in mm and angular dimensions in degrees. The offset of the main mirror is marked in the direction perpendicular to the telescope boresight.

3.1 The telescope and baffling system

The telescope (see Figure 1b) consists of an off-axis tilted Gregorian system, offering the advantages of no blockage and compactness. The eccentricity and tilt angle of the secondary mirror, and the off-axis angle obey the so-called Dragone-Mizuguchi condition, which allows the system to operate without significant degradation in a large focal plane array, while simultaneously minimizing the polarization effects introduced by the telescope.

The baffling system is composed of two elements. The first (the "shield") is a large, self-supporting, and roughly conical structure covered with MLI, which surrounds the telescope and focal plane instruments. Together with the payload platform or optical bench, it defines the payload (or optical) "enclosure" (see Figure 1). It has an important function in reducing the level of straylight (which at the chosen orbit is in large part due to the spacecraft itself) and in promoting the radiative cooling of the enclosure towards deep space. The second element (the "baffle") consists of one half of a conically shaped surface that links the focal plane instruments to the bottom edge of the subreflector; its function is to shield the detectors from thermal radiation originating within the enclosure.

The primary and secondary mirrors will be fabricated using Carbon Fibre (CFRP) technology, taking advantage of the experience accumulated in the design and development of the FIRST (the Far Infrared and Submillimetre Telescope, an ESA cornerstone mission) telescope.

3.2 The Low Frequency Instrument

The LFI (see Figure 2) is designed to cover the 30 - 135 GHz band, with an array of 56 detectors split into 4 channels, centered at 31.5, 53, 90, and 125 GHz. Radiation will be coupled from the telescope to the detectors via conical corrugated feedhorns exploiting the two orthogonal polarizations at a given frequency. Thus, each horn feeds two receivers. Each receiver consists of a pair of amplification/detection chains connected in parallel via so-called hybrid rings, and constitutes a "continuous-comparison" device. In this scheme, the difference between the inputs to each of the chains (the signal from the telescope and that from a reference blackbody respectively) is continuously being observed. Each amplification stage will be provided by High Electron Mobility Transistors (HEMTs). This technology offers at present the best compromise between sensitivity and ease of implementation in the frequency range of the LFI. Total power receivers based on Monolithic Microwave Integrated Circuit (MMIC) technology, in which the whole receiver is packed into a device a few centimeters across, are state-of-the-art but already available commercially with characteristics close to those required by COBRAS/SAMBA .

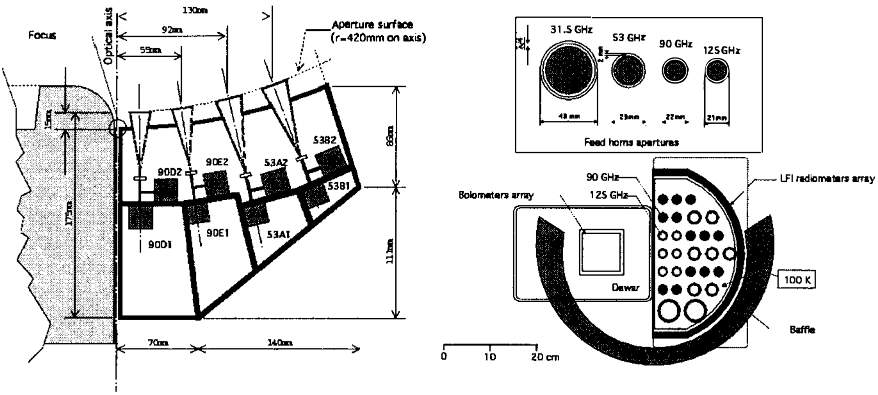

Figure 2: Side and top view of the LFI, the former showing the horn/receiver arrangement, and the latter the layout of the feed apertures in the focal plane.

3.3 The High Frequency Instrument

The HFI (see Figure 3) will cover the high frequency part of the COBRAS/SAMBA range. The heart of the HFI – the detectors – are bolometers, solid-state devices in which the incoming radiation dissipates its energy as heat that increases the temperature of a thermometer. For a bolometer, the temperature increase is inversely proportional to the heat capacity of the bolometer. The cooling of these detectors to very low temperatures provides for the low heat capacity needed for high sensitivities. In the case of COBRAS/SAMBA , the HFI bolometers must be cooled to temperatures of ~ 0.1 K.

The total number of bolometers will be 56, split into 5 channels at central frequencies of 143, 217, 353, 545, and 857 GHz. The placement of the channels in frequency space has been optimized

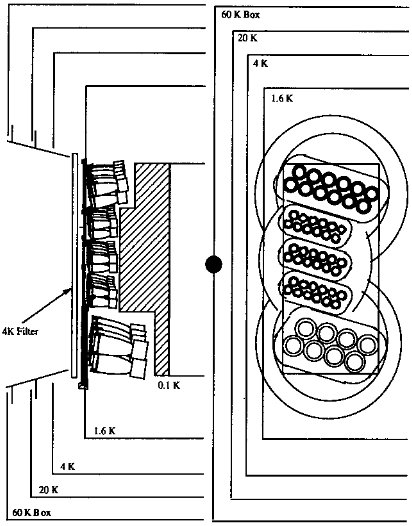

Figure 3: A conceptual view of the HFI "cold box", which consists of nested radiation shields maintained at various temperatures by the active cooling system. The side view shows the optical arrangement, including the 4 K blocking and 1.6 K bandpass filters, and the Winston cones. The top view shows the detector layout and filter outlines.

not only to remove the foregrounds (mainly dust emission at these high frequencies) and recover the CMB, but also for the detection of the Sunyaev-Zeldovich effect. Filters provide the necessary frequency selectivity for each channel, and also block the thermal radiation coming from the telescope itself. Light from the telescope will enter the cold box through an initial blocking stage at 4 K, proceed through a second bandpass filter at 1.6 K made from interfering cross-shaped grids embedded in a polyethylene matrix, and will finally be concentrated on the detectors by Winston cones. The entrance apertures of the cones define the fields of view of the detectors; they are sized to the diffraction pattern in the three low frequency channels, and oversized in the two highest frequency channels in order to cope with the aberrations of the telescope. The bolometers are read out via J-FETs located very close to them, in a box which is physically located inside the cold box of the HFI, but thermally insulated from it. The readout electronics are based on the principle of AC bias that has successfully demonstrated (in ground-based experiments) its capability to detect signals at very low frequency without sky-chopping.

The low temperature required by the bolometers (0.1 K) must be provided by an active cooling system, which will consist of a number of Stirling-cycle mechanical coolers coupled to an open-cycle He dilution refrigerator. The mechanical coolers will provide precooling of ^{3}He and ^{4}He cryogen down to 4 K, as well as control of the temperature of the outermost radiation shield of the HFI to ~65 K; the dilution system (consisting of an initial Joule-Thompson stage followed by the ^{3}He/^{4}He dilution refrigerator) carries the cooling down to 0.1 K. The overall system is very similar to that which will be used by FIRST (an approved ESA cornerstone mission).

The basis of the COBRAS/SAMBA mechanical cooler technology is the development by Oxford University and Rutherford Appleton Laboratory (RAL) of an 80 K cooler that was space qualified for the ISAMS instrument, and the further development at RAL of a two stage Stirling Cycle Cooler achieving 20-50 K, and a closed cycle Joule-Thomson Expansion Cooler achieving 4 K. British Aerospace (now Matra Marconi Space), funded by ESA, has successfully transferred this technology to an industrial level and can provide space qualified 4 K coolers. The long life and high reliability of these systems result from the use of a frictionless compressor that has demonstrated successful space operation for periods of years.

The Open Cycle Dilution/Joule-Thomson Refrigerator has been developed at the Centre de Recherches des Très Basses Temperatures (CRTBT) in Grenoble (France). It uses a new dilution principle based on friction that does not need gravity to operate. Its cooling power depends on the gas flow, which is very low and thus allows sufficient gas storage to achieve long mission life. The principle of this cryogenic architecture and its ±1 g operation have been successfully proven with a demonstration model, and qualification of this system for space operation is in progress.

4 Payload Requirements

In addition to requiring large sky coverage, instrumental effects demand that the observing pattern be repetitive with a periodicity of order 1 minute. These requirements indicate a solution in which the telescope line of sight sweeps large areas of the sky periodically with a period of ~1 minute. This situation is most naturally arrived at with a spinning spacecraft where the telescope line-of-sight is offset from the spin axis by an angle (the so-called "scan angle" -70° - see Fig. 1), and thereby describes a circle on the sky. A spinning period of 1 r.p.m. fulfills the one minute periodicity requirement.

The control of straylight and thermal variations imposes severe constraints on the payload. Variations can be either random or systematic (e.g. synchronized with the observing pattern); the latter are the most severe since their effect does not average out by integration. Simulation of the instrumental sensitivity to temperature fluctuations of critical components results in stability requirements of a fraction of a milliKelvin for the optical surfaces and elements in the focal plane.

The main source of systematic temperature variations within the payload enclosure is spin-synchronized modulation of solar illumination on the spacecraft. The optimal situation is encountered when the payload is permanently maintained in solar shadow, and the spin axis is parallel to the Sunwards vector. This condition can be met if the payload is pointed in the anti-Sun direction and thus protected from direct solar illumination by the rest of the spacecraft, and in addition, if the motion of the spin axis is restricted to comply with the shadow condition. From the latter, it follows that to obtain the required sky coverage the scan angle (i.e. the angle between the spin axis and the viewing direction) must be large (e.g. 90° corresponds to tracing meridian circles on the sky, and achieving full sky coverage). Secondary sources of thermal modulation of the focal plane are caused by passages of the Earth and Moon through the field of view. These must be reduced by the choice of orbit.

One of the most significant issues in the payload design is to achieve adequate rejection of unwanted radiation, which include local (satellite) sources and Solar System sources. The requirements in this area are met not only by appropriate optical design, but also by specifying the allowed orientation of the spacecraft with respect to the major sources of straylight. The rejection required of the brightest source, the Sun, is ~93 dB at the most critical frequency (31.5 GHz). For the next brightest sources, Earth, Moon and Jupiter, the rejection requirements are 79 dB, 67 dB and 43 dB, respectively (assuming a sensitivity of order $\Delta T/T \sim 10^{-6}$). Due to the orientation possibilities of the spin axis, these requirements mean that the radiation suppression should be better than ~-93 dB for $\theta > 165°$ and better than ~-67 dB for $\theta > 150°$ (θ being the angle from the spin axis). The required rejection is of course most easily achieved if the enclosure is continuously pointed diametrically away from the Sun. Detailed electromagnetic simulations of the optical enclosure, which take into account the angular response of individual detectors, have shown that by combining an appropriate optical design and observing strategy, it will be possible to cope with the straylight problem adequately.

A compromise between achieving large sky coverage, maintaining thermal stability, and rejecting solar straylight, results in a choice of scan angle of 70° . The geometry of the spacecraft (constrained by the launcher fairing) is such that the payload will remain in the shadow of the Sun for spin-axis to Sun-vector angles of up to 15° . Thus, ecliptic latitudes as large as ±85 degrees will be available for observation, or more than 99% of the whole sky.

The basic anti-Sun pointing strategy reduces the effects of solar radiation to a minimum; however, the Earth and Moon can also be intense sources of both straylight and thermal modulation, and reducing their effects drives the choice of orbit. Near-Earth orbits are eliminated mainly because the large thermal influx renders it extremely difficult to reach temperatures near 100 K in the focal plane, or to achieve the required thermal stability and straylight rejection. The nearest far-Earth orbit possible is that around one of the Lagrangian points of the Earth-Moon system (L4 or L5); this orbit (which shares the Lunar motion around the Earth) suffers from the fact that the Earth or the Moon are often not very far from the telescope line-of-sight. Simulations indicate that if this orbit were chosen, at least 35% of the acquired data would have to be discarded due to poor thermal or straylight conditions, leading not only to lower sky coverage but also to a less efficient removal of systematic effects. The optimal choice of orbit, resulting from a tradeoff of the various payload requirements, several spacecraft technical constraints (most importantly related to telecommunications to ground), and the transfer-to-orbit cost, is a Lissajous orbit around the L2 Lagrangian point of the Earth-Sun system. At this location, the Sun, the Earth, and the Moon are all located behind the payload, where their undesirable effects are at the lowest possible level, both in terms of location and of flux. In addition, this is the only orbit in which the antennas which provide telemetry and telecommand (TM/TC) for the spacecraft are also continually pointed away from the payload, thereby minimizing the potential effects of RF interference.

5 Mission aspects

COBRAS/SAMBA is designed to fit into the lowest cost launch scenario available after the year 2003 for ESA space science missions, i.e.:

- it will be one of two (or three, if this option is available) passengers on an Ariane 5 launcher;
- the launch window and target transfer orbit are dictated by the most likely co-passenger(s) - telecommunications satellites in geostationary orbits - rather than by COBRAS/SAMBA itself.

More specifically, the Ariane vehicle will inject COBRAS/SAMBA into the standard Geostationary Transfer Orbit, and transfer and injection into the final operational orbit will be accomplished using the on-board propulsion system of the spacecraft. The best-case transfer trajectory, lasting approximately 6 months, is shown in Figure 4.

As mentioned before, the operational orbit will be a Lissajous orbit around the L2 point of the Earth-Sun system; the semi-major amplitude of the orbit will be ~400,000×100,000 km. In this orbit COBRAS/SAMBA will move around the L2 point with a period of about 180 days.

6 The Observing Plan

The basic observing strategy is based on the antisolar orientation of the spin axis, as outlined previously. To maintain this orientation, the spin axis must be displaced along the ecliptic plane by 1° every day. This is done in individual steps for ease of operations. An appropriate value for the amplitude of each step is $5'$; thus, the basic plan consists of one $5'$ displacement of the spin axis along the ecliptic plane every 2 hours.

A perturbation to the basic motion along the ecliptic plane will be purposely introduced to optimize the distribution of integration time (and thus of achieved sensitivity level) over the sky. The strategy is to add to the basic ($5'$) ecliptic-plane manoeuver a component which brings the spin axis out of the ecliptic plane, by an amount which is to first order sinusoidal with time, has a period of order months, and a maximum amplitude of 15° .

The scan angle of 70° implies that one (>90%) sky coverage can be achieved after ~7.3 months of observations. The need to control systematic effects requires that at least two full sky coverages be achieved. This sets the minimum mission duration as that allowing routine observations of more than ~15 months, although clearly a longer duration of operations is desirable as it would lead to increased sensitivity, and better control of systematics.

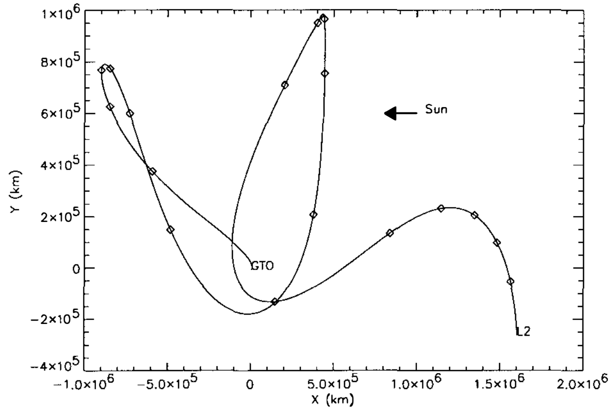

Figure 4: Best case transfer trajectory from Geostationary Transfer Orbit (GTO) to a Lissajous orbit (projection onto ecliptic plane, launch on 3 March 2003). Ticks are marked along the trajectory at 10 day intervals, starting at launch. Orbital motion within GTO is not shown in this plot. In most transfer cases, an inclination change manoeuver occurs about 30 days after launch, and a final injection manoeuver about 6 months after launch.

7 Scientific Operations

Routine scientific operations will commence during transfer to L2, approximately 3 months after launch, or 4 months before insertion into the Lissajous orbit. Once routine operations are initiated, the observing mode will be unique. Routine operations will be tied to the period of visibility afforded by one ground station (Kourou), which varies according to the season between 10.1 and 11 hours. During the visibility period, the data of the preceding obscuration period will be telemetered to ground, interleaved with the ongoing observations. During routine operations, the spacecraft will operate in a pre-programmed, automatic manner. The observing pattern (consisting of a series of manoeuvers to be carried out at 2 hour intervals) will be known far in advance.

Calibration of the science data (both absolute and relative) will not require a special mode of operation, but will be an ongoing process during sky observations. Various sources will be used for this purpose, most notably the well-known dipole component of the CMB, passages through the galactic plane, extragalactic point sources, and planets present in or near the field of view (Jupiter, Saturn, Mars). At high frequencies the absolute calibration will be tied to COBE-FIRAS observations of the galactic plane.

8 Scientific Data Products

Final data processing consists mainly of two steps: generation of maps of the surveyed area from the raw data, and separation of the various components from the maps to obtain both the cosmological signal, and the foreground emissions.

There will be three levels of scientific data products:

1. time series of the data acquired by each detector, after basic calibration, removal of systematic features, and attitude reconstruction;
2. maps of the sky in nine frequency bands;
3. maps of the sky for each of the main underlying components (CMB, SZ, dust, free-free, and possibly synchrotron).

9 The Spacecraft

Two separate modules, the payload module (PLM) and the service module (SVM) have been conceived to keep simple and clear interfaces, thus optimizing the development, integration and testing activities (see Figure 5).

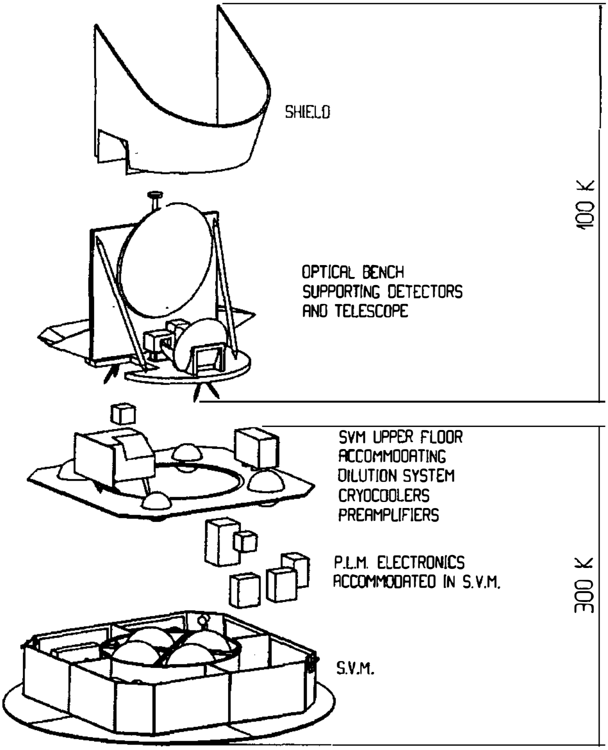

Figure 5: A three-dimensional exploded view of the spacecraft.

The PLM houses all the payload equipments requiring cryogenic temperatures : the detection units of the instruments, the telescope, the baffle and the outer flared shield. All this is mounted on a cold optical bench, together with a cryogenic radiator of nearly 3 m^2, fixed vertically onto the main mirror support. The optical bench is attached to the SVM top platform by means of glass fiber struts. Cryo coolers and cryogenic dilution system equipment are also mounted on this top platform, and the whole constitutes a mechanically and thermally autonomous assembly.

The SVM houses all the warm electronics of the payload, together with the subsystems of the spacecraft. It is a flat octagonal box, whose design is driven by the need to maximize inertia about the spin axis. All equipments are attached to lateral walls, which simplifies their passive thermal control. Four fuel tanks are accommodated inside the central cylinder. The solar array is fixed, non deployable, and of annular shape. Its outer diameter is 4 m, the maximum allowable for the Ariane 5 SILMA fairing. It is mounted at the base of the SVM, with the active side facing away from the SVM and PLM.