The FIRST and Planck "Carrier" missions. Description of the cryogenic systems.

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Abstract

ESA has investigated the possibility to merge two of the next scientific missions of its HORIZON 2000 Programme, the fourth cornerstone mission, the Far InfraRed and Sub-millimetre Telescope (FIRST) and the third Medium-sized Mission M3, Planck (formerly Cobras/Samba).

FIRST is a multi-user observatory, which targets the infrared and sub-millimetre part of the electromagnetic spectrum, covering approximately the wavelength range from 80 µm to 670 µm. The Planck mission is a survey mission dedicated to mapping the temperature anisotropies of the cosmic background radiation.

The merging of the missions was studied in view of the programmatic constraints on both missions, the fact that they use a similar orbit (around the 2nd Lagrangian libration point L2), the partial parallel development of both missions and the potential cost savings. The decision taken during the ESA Science Programme Committee (SPC) meeting held end of May 98 is that the two missions will be implemented in the so-called "Carrier" solution. Both satellites will designed and launched together, and then will be separated.

The cryogenic system of FIRST is based on a Superfluid Helium Dewar at 1.65 K (Infrared Space Observatory - ISO technology) with a design lifetime of more than 3 years. The very low temperature (0.3 K), required in the bolometer instrument will be obtained from a dedicated 3He-sorption cooler. The cryogenic system of Planck uses a sequence of passive radiator (60 K), H2 Joule-Thomson (JT) Sorption cooler (20 K), JT mechanical cooler (4 K), and dilution refrigerator (0.1 K).

Keywords: FIRST, Planck, cryogenics, sorption refrigerator, dilution refrigerator.

1: Introduction

FIRST (1,3,4,14), the Far InfraRed and Sub-millimetre Telescope is the fourth European Space Agency (ESA) cornerstone mission in its long-term scientific plan Horizon 2000. It is dedicated to perform astronomical observations in the far-infrared and sub-millimetre wavelength range. FIRST is a multi-user observatory type mission. It has a cold and low emissive telescope. The detectors of the FIRST instruments have to be cooled to cryogenic temperatures in the range of 0.3 to 2 K in order to reach the necessary sensitivity for the observation of a variety of weak radiation sources.

Planck (2,5) (formerly Cobras/Samba) is the third ESA's Medium Size mission (M3). The main objective of the Planck mission is to image the temperature anisotropies of the Cosmic Microwave Background (CMB) over the whole sky with a sensitivity of ΔT/T = 2. 10^-6 and an angular resolution of 10 arc-minutes. This observation requires a cryogenic temperature of 0.1 K for the bolometers, 20 K for the HEMT (High Electron Mobility Transistors) instrument, and also a cold and low emissive telescope.

A number of similarities between the two missions have raised the question of whether there is a technical solution that combines both payloads onboard one spacecraft, while preserving the scientific capabilities. This paper describes the present spacecraft design that has been established in the framework of two parallel ESA studies. The two feasibility studies, performed by European industry (Aerospatiale, Matra-Marconi-Space and Dornier Satelliten Systeme) under the leadership of ESA, and in collaboration with the scientific community involved in the mission and the future instruments, started in mid 1997 and were completed in early 1998.

The technical approach that has been examined for the cryogenic subsystems of the spacecraft, i.e. those subsystems that provide the proper environment to the payloads, is presented below. The spacecraft design is built up in a modular way: there is a separation between the FIRST Payload Module and the Planck Payload Module (PPLM). Both Cryogenic Modules are described

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The FIRST payload module is derived from the cryogenic system of the ISO spacecraft and many similarities can be found. The Planck Payload Module provides passive cooling to a temperature of around 60 K. From this temperature active coolers are used as part of the scientific instruments to cool detectors down to 0.1 K. The SerVice Modules (SVM) that provides all relevant spacecraft functions is not described in detail in this paper.

The FIRST/Planck mission is briefly summarised in section 2 and the baseline spacecraft concept described. The cryogenic systems of the FIRST and Planck Payload Modules are described in greater depth thereafter. The overall design and functional description is given together with the results of the thermal and structural analyses. The spacecraft development phase is illustrated in section 5 with emphasis on the tests of the cryogenic systems.

2: The Mission and the two Spacecraft

A spacecraft design has been found, accommodating both model payloads. These model payloads used during this definition study were defined by the FIRST / Planck Science working group. The latest definition of the instruments is presented in ref. (14).

**FIRST Scientific Objectives and Model Payload.**

The prime scientific objectives of the “FIRST mission” are:

- Deep broadband photometric and spectroscopic surveys
- Follow up spectroscopy of objects discovered in the photometric survey
- Physics and chemistry of interstellar medium
- Observational astro-chemistry
- High spectral resolution of comets and planetary atmospheres.

These objectives will be achieved by a set of three instruments,

- **HIFI (Heterodyne Instrument for FIRST),** a heterodyne instrument, performing high and very high-resolution spectroscopy (250 µm to 600 µm). The mixers in HIFI need to be operated at around 2 K.

- **PACS (Photo-conductor Array Camera & Spectrometer),** an incoherent photo-conductor instrument, performing imaging line spectroscopy and photometry (80 µm to 210 µm). The detectors need to be cooled to around 1.7 K.

SPIRE (Spectral & Photometric Imaging Receiver), an incoherent bolometer instrument, performing photometry simultaneously in three bands, and spectroscopy across the whole wavelength range (200 µm – 670 µm). The bolometers will be operated at a temperature around 0.3 K.

**Planck Scientific Objectives and Model Payload.**

The prime scientific objectives for the “Planck mission” are

- CMB anisotropy measurements with accuracy of $\Delta T/T = 2 \times 10^{-6}$
- Tests of inflationary models of the early universe
- Characteristic signatures in the CMB created by topological defects
- Amplitude of Structures in the CMB
- Measurement of Sunyaev-Zeldovich effect
- Production of high sensitivity maps of the sky in the observation wavelengths

There are two instruments base-lined for Planck:

- **High Frequency Instrument (HFI),** a bolometer instrument (160 GHz to 900 GHz). The bolometers will be operated at a temperature of 0.1 K.

- **Low Frequency Instrument (LFI),** an array of tuned radio receivers based on HEMT. These receivers will be operated at a temperature of about 20 K (total dissipation: 550 mW).

The selection of the FIRST and Planck payload instruments has been provisionally endorsed by the SPC on 28-29 May 1998.

**Satellites description**

Different scenarios have been analysed on the implementation of the FIRST and Planck missions (see figure 2-1). The alternatives range from (i) two separate spacecraft, launched in two years of each other (“Planck alone” and “FIRST alone”), to two spacecraft launched on the same launcher but separated early after injection into the transfer orbit (the “Carrier Concept”), (iii) the “merged spacecraft” or “Merger” where both payloads are accommodated onboard one spacecraft. The cooling systems are very similar in these 3 options. The studies concluded to the technical feasibility of the 3 options, with the same scientific return, but different cost (“Merger”, “Carrier”, alone, in increasing order). The independent mission scenario has been disregarded mainly due to its higher cost. Finally, during the ESA SPC meeting in May 98, the “Carrier” solution has been
recommended for implementation rather than the "Merger", allowing a better optimisation of the spacecraft, less development risks, and offering more flexibility for the now independents mission. The present paper describes this "Carrier" version.

The FIRST-Planck "Carrier" design concept is shown in figure 2-2. The two spacecraft are mounted on the top of each other in the Ariane V fairing, Planck carrying FIRST. The mechanical interface between the 2 satellites is a clamp band, similar to the one between Planck and the launcher. A supporting cylinder will remain attached to FIRST after separation.

FIRST is a 3 axis stabilised spacecraft, using a similar design than ISO, whose heritage will be the cryostat, and the satellite architecture. It is composed of 2 main modules: the FIRST Payload Module (FPLM) including the telescope and the cryostat, and the SVM (SerVice Module). The telescope, unlike ISO, is located outside of the cryostat. The telescope and cryostat are shadowed from the sun radiation by the Sunshield that carries also the solar array. At a given time, only a band of 60° of the sky is visible because of the ±30° attitude constraint with respect to the sun direction.

The FIRST telescope is a 3.5 m diameter Cassegrain system, with very low emissivity (0.05), operating at an orbital temperature of 70 K to 90 K. The focal plane units of the three scientific instruments are located inside the cryostat. The temperature of the outer shell of the cryostat has been estimated to be similar to that of the telescope at around 80 K. The FIRST SVM is mounted below the FPLM and carries all spacecraft electronics and those instrument units that operate in an ambient temperature environment.

Below, the Planck spacecraft is also composed of 2 modules: a SVM, and the Planck Payload Module

Figure 2-2:FIRST and Planck "Carrier" before and after separation
(PPLM). The SVM carrying also the solar array on the back is used to shadow the PPLM. Planck will be spin at about 1 rpm around the sun direction (±10°).

The PPLM is passively cooled down to temperature of 50-60 K. The common Focal Plane of both Planck instruments is mounted to a radiator / optical bench that also carries the Planck telescope (an off-axis Gregorian telescope with 1.5 m effective aperture, tilted at about 80° from the spin axis). The further cool down to 20 K for the LFI, respectively 0.1 K for the HFI is performed by additional coolers that are part of the scientific instruments.

Both spacecraft will be observing autonomously for a period of 20 to 22 hours a day, collecting the scientific data in a solid state recorder onboard. During the ground contact time of 2 to 4 hours the stored data is transmitted to ground and the observatory programme for the next day uploaded.

The total expected lifetime for scientific is 3 years for FIRST, and 1.5 years for Planck (allowing 2 complete sky scans).

In summary the characteristics of the satellites are:

**FIRST**
- Dimensions: height 7.5 m ø 4.5 m
- FIRST telescope diameter: 3.5 m
- Total mass: 3100 kg
- Solar array power: 1310 W (incl. 450 W for telescope decontamination used at the start of the mission)
- In orbit science lifetime: 3 years
- AOCS: 3 axes stabilised

**Planck:**
- Dimensions: height 3.8 m ø 4.5 m
- Planck Telescope: 1.5 m (effective aperture)
- Total mass: 1450 kg
- Solar array power: 1200 W
- In orbit science lifetime: 3 years
- AOCS: Spin (1rpm)

**FIRST + Planck in Launch configuration:**
- Dimensions: height 10 m ø 4.5 m
- Total mass: 4750 kg (incl. launcher interface + extra margin)

**Orbits**
The FIRST and Planck satellites will be launched together by an ARIANE 5 launch vehicle from Kourou. After burnout and separation from the lower ARIANE composite, FIRST is separated, and continues its way to a large Lissajou (diameter 900000 km) orbit around the second Lagrangian Point L₂. Then the upper stage is reignited to send Planck to a small Lissajou orbit (diameter 300000 km) around the same point L₂. The spacecraft will acquire their final orbital positions at around 1.5 million-km from the earth after a transfer time of approximately six months. Orbits around the L₂ are unstable and without orbit corrections the spacecraft would deviate exponentially from the nominal one. Small correction manoeuvres, applied in monthly intervals will, however, maintain the orbit close to the nominal one. From the cryogenic point of view, the main advantage of such orbit is the fact that the earth infra-red radiation is small, and that the earth and the sun are together nearly in the same direction, allowing to obtain passively a low and stable temperature. The size of the Planck orbits around the second Lagrangian point have been selected in order to allow the use of a fixed antenna telecom system and to keep the background straylight level of the earth low enough.

**3: Cryogenic System for FIRST**

**Design Overview**
The satellite is providing a cooling system based on the ISO technology (13). It is a large superfluid Helium Dewar (helium at 1.65 K), sized for the scientific mission. The current situation in that the FIRST cryostat is still designed for the "Merger" configuration (4.5 years). This margin in the lifetime can be used to reduce the cryostat size (an horizontal slice of 450 mm can be removed), or to give some flexibility for the instrument accommodation. The current volume of the super-fluid Helium tank is 2560 litres. Further cooling down to 0.3 K for the bolometers is provided by the instrument with a ³He sorption cooler (6), directly connected to the main He tank.

The use of ISO technology to the maximum extent possible was one of the drivers in the selection of a cryogen system for FIRST, in order to reduce the development risks and costs.

In absence of gravity, the liquid Helium is maintained inside the tank by means of a phase separator (sintered steel plug) which uses the fountain effect of the super-fluid helium to retain the evaporating interface inside the plug. The enthalpy of the gas is efficiently used to cool part of the instruments (4 K and 15 K stages), and the 3 thermal shields.

The space side of the Cryostat Vacuum Vessel (CVV, which provide vacuum insulation for ground operation) is used as a radiator area to cool the CVV on orbit to a final equilibrium temperature of about 80 K. This radiator area is coated with black paint to achieve low temperatures in the L₂ orbit. All other outer CVV-surfaces are covered by Multi-Layer-Insulation (MLI), in order to insulate it from the warm items (SVM, Sunshield). The outer layer of the MLI is optimised for the lowest temperature of the CVV.
The items that are mounted to the outside of the cryostat are:

- Telescope (3.5 m diameter primary mirror, 60-80 K)
- Local Oscillator Box (LO, 100-140 K)
- Star-tracker Housing (STR-H) with 3 Star-trackers and their baffles (room temperature)
- Solar array (350 K)

The CVV-diameter and the lower CVV-bulkhead form are identical to that of the ISO Cryostat, as well as the form, location and detail design of the SVM/PLM fixation struts interface area. Since the CVV-diameter is that of ISO, the CVV-wall thickness of the lower bulkhead, the cylinder and the upper bulkhead, at least in its cylindrical part is the same as those of the ISO-CVV. Only the curved part of the upper CVV-bulkhead has a slightly larger wall thickness than the ISO-CVV-upper bulkhead curved part, because the radius of curvature for the FIRST-CVV must be larger than that of ISO as a consequence of the telescope focus position and the required scientific instruments height.

The CVV-cylinder is shorter than the ISO-cylinder, since the FIRST-He II-tank is shorter than the ISO-tank, although it has a slightly larger volume. Further more the height of the structural supports above and below the tank are adapted to this configuration.

The cryostat is shown in more detail in figure 3-1

This cryostat consists of the following items:

- A segmented cylindrical main He II-tank of 2560 l cold volume, equipped with all the necessary components such as valves and phase separator, technology directly transferred from ISO
- A lens-shaped (ellipsoidal) 79 l auxiliary He-tank for launch autonomy cooling
- A carbon-fibre-compound (CFC)/sandwich Optical Bench (OB) for the mounting of the 3 scientific instruments, equipped with two He-vent gas cooled heat exchangers for the “4 K- and 15 K-instruments cooling stages”
- A common instruments protection shield, mounted to the OB
- 3 vapour-cooled radiation shields, each consisting of 3 parts (the main cylindrical part being the actively cooled part). Each shield being equipped with MLI. Each upper shield performs a part of the telescope inlet beam baffling system.
- 16 tank support straps, each consisting of 4 GFC- and 2 CFC-chain loops inter-linked by steel bolts which act as thermal anchors and a mechanical support of the heat shields with the corresponding straps tensioning devices

The cryostat is closed on ground by a cryostat cover that opens on orbit for entrance of the telescope beam. Around the cover is a cooled cavity for straylight suppression.

**He subsystem**

The He-subsystem is represented by its He-flow schematic on figure. 3-2.

The He-subsystem has the same purpose as in ISO, with the essential task being the cooling of the scientific instruments and the cryostat thermal shields. This cooling is represented in figure. 3-2 by two heat exchangers, one for the „4.3 K“-stage and one for the „15 K“-stage. The cooling of the „1.7 K“-stage in the scientific instruments...
is done by direct coupling to the He II-tank by one Ag-thermal braid per instrument.

The FIRST-cryostat He II-tank is a segmented cylindrical tank. The tank segmentation is necessary in order to achieve a sufficiently high eigenfrequency by reducing the liquid helium compression oscillation wavelength.

The segmented He II-tank is machined out of AlMg4.5Mn and shown in the centre of figure 3-1.

The auxiliary He tank (normal He at 4.2 K) is structurally fixed by Titanium alloy blade springs to the middle brackets at the lower Spatial Framework, i.e. it is located below the He II-tank. This auxiliary tank is used during the last 6 days before the launch, when the external pumps have to be stopped and the main tank is closed. By evaporating helium at 1 bar, it maintains cooling of the shields and limits the warming up of the tank.

**Cryostat Cover Subsystem**

The purpose of the cover is to be able operate the cryostat on ground, with an internal insulation vacuum. It has to open just once, after few days in orbit, when sufficient outgassing of the satellite has been achieved.

The cryostat cover for FIRST is to be based on a derivative from the cover of the IBSS (Infrared Background Signature Survey) cryostat, which was already successfully flown on the Space Shuttle flight STS 39 in May 1991.

The cryostat cover itself consists of an outer vacuum-tight shell, and a thermal radiation shield on its inner side. On ground, the radiative cooling of the cover-internal thermal shield lowers its temperature to approximately, 231 K (-42°C).

### Analyses

#### Structural Analysis

The structural analysis of the FIRST-PLM was done by a frequency response analysis. The calculated first axial FPLM eigenfrequency is at 43 Hz, the first lateral eigenfrequency at 30 Hz. This structural performance is adequate for FIRST/Planck.

#### Thermal Analysis

Thermal models of the cryostat have been done, starting from the ISO models. The are used to assist the design, and to predict the temperature levels and heat budget in all steady state conditions (Ground and orbit), the transient (launch autonomy, launch, and post launch transient), and the life-time (from the integral of helium consumption since launch)

The FIRST PLM thermal model is managed by the PLM contractor (DSS). It is build with ESATAN, has about 250 thermal nodes. In addition to a detailed description of the inside of the cryostat, it includes also all conductive and radiative couplings to the SVM, Sunshield and Telescope being considered as boundary nodes.

For the post-launch transient, i.e. the cool-down of the CVV and the establishment of orbital equilibrium, a simplified model, based on ISO data, could be used.

The comparison of the prediction for ISO and FIRST, and some measured flight data of ISO are given in table 3-1.

Figure 3-3 gives the heat budget of the ISO and FIRST Helium tanks. This gives some clarification about the performance improvement. We see that ISO lifetime was completely dominated by the conduction along the tank support straps. The segmented tank (see above) allows using thinner straps and reducing this contribution from 80% to 50%. The rest of the improvement is mainly due

### Table 3-1: FIRST Cryostat temperature distribution for Ground Equilibrium and Orbit Equilibrium:

<table>
<thead>
<tr>
<th></th>
<th>ISO (prediction)</th>
<th>ISO (Measured)</th>
<th>FIRST (prediction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVV</td>
<td>116</td>
<td>113</td>
<td>77 K</td>
</tr>
<tr>
<td>3rd shield</td>
<td>78</td>
<td>80.5</td>
<td>62 K</td>
</tr>
<tr>
<td>2nd shield</td>
<td>45</td>
<td>53.3</td>
<td>43 K</td>
</tr>
<tr>
<td>1st shield</td>
<td>27</td>
<td>22.5</td>
<td>30 K</td>
</tr>
<tr>
<td>spatial framework</td>
<td>17</td>
<td>15.9</td>
<td>11.7 K</td>
</tr>
<tr>
<td>15K Heat exchanger</td>
<td>9.5</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>4K Heat exchanger</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tank</td>
<td>1.82</td>
<td>1.734</td>
<td>1.65 K</td>
</tr>
<tr>
<td>heat load on tank</td>
<td>0.114</td>
<td>0.095</td>
<td>0.045 W</td>
</tr>
<tr>
<td>mass flow</td>
<td>4.934</td>
<td>4.17</td>
<td>2 mg/s</td>
</tr>
<tr>
<td>initial mass</td>
<td>513</td>
<td>531</td>
<td>553 kg</td>
</tr>
<tr>
<td>Mass loss during transient (40 days)</td>
<td>36.3</td>
<td>31.3</td>
<td>38.4 kg</td>
</tr>
</tbody>
</table>
to the colder temperature of the CVV, due to its radiator. This radiator could not be used on ISO, because of the influence of the earth radiation on the temperature fluctuation of the CVV, and consequently on the telescope alignment stability.

**Operations and mission**

**Launch Autonomy**

The He II-tank (closed) heat load with different He mass flow rates from the He I-tank was calculated. The foreseen sequence assumes a refill of the He I-tank every 48 hours. This allows a mass flow rate of around 50 mg/s and keeps the He II tank environment sufficiently cool to reach the required launch autonomy of 6 days.

**Post Launch Transient**

The He II-bath temperature is expected to increase and then decrease immediately after launch. The total He consumption during the first 40 mission days (up to equilibrium) has been estimated from the transient mass flow rate to be $\Delta m_{\text{HeII}} = 38.4$ kg.

**Operational Lifetime**

The operational lifetime (OLT) is determined by the use of the initial He II-filling at launch (assuming a 98% filling level), the He consumption during the first 40 mission days ($\Delta m = 38.4$ kg) and the orbit equilibrium mass flow rate. The resulting OLT is calculated with the above values to be about 5 years (still designed for the "Merger" mission of 4.5 years).

During this period, the temperature of the tank should be more stable than that of ISO, shown on figure 3-4: The main fluctuation is a seasonal effect due to the earth IR radiation, plus the peaks (5 mK) associated with DLCM, and one due to an accidental earth constraint violation.

**4: Cryogenic System for Planck**

The cryogenic system of Planck does not benefit of a previous flight experience, and therefore, more efforts will be required for the development phase.

**Design overview**

Planck architecture is also mainly driven by the optical and thermal requirements. The fact that the Planck and FIRST cooling systems are completely different is mainly due to historical background. It was not possible to put all the 5 instruments in the same cryostat, mainly because of the incompatibilities between the optics, and of the attitude requirements.

The architecture of the spacecraft has been optimised to benefit of the passive cooling in the $L_2$ orbit. The Solar Array/Sunshield (350 K), and the SVM (300 K) are used to shield the payload module from the sun, and to provide the large inertia around the spin axis. The PPLM is insulated as much as possible from the warm parts.

The thermal environment for the instrument detectors and optics is obtained by a sequence of coolers as follows:

- Pre-cooling to $\sim 60$ K for all active coolers by means of a large radiator.
- Cooling to 18 K-20 K for LFI and pre-cooling for HFI with a $\text{H}_2$ Joule-Thomson Cooler with
adsorption compressors (called H₂ sorption cooler), and part of the instruments.

- Cooling to 4 K with a Helium Joule Thomson cooler with mechanical compressors provided by the HFI instrument.
- Cooling at 1.6 and 0.1 K with an open loop dilution refrigerator (provided by the HFI instrument).

**Active coolers for Planck**

The required cryogenic environment of the LFI instrument mainly dictates the organisation of Planck PLM. A relatively high dissipation of 550 mW for the front end at 20 K, a large number of wave guides between this front end and the back end at 300 K, and the necessary supports, cable and margins results in a heat lift requirement of 1.2 W at 20 K. This can be handled by the 20 K sorption coolers developed by JPL, whose principle has been demonstrated in the BETSCE experiment (7). This is a Joule Thomson cooler, using H₂ as the working fluid. Several sorbent beds that are used alternatively at high temperature (60 bar for 485 K) or low temperature (0.4 bar at 280 K) to provide the high and low pressure reservoirs. The adjustment of the cooling power of this cooler to the required heat lift and the actual radiator environment is done by selecting the mass flow rate, or the volume of the sorbent bed.

The sorption cooler requires a pre-cooling of the H₂ gas at least below the inversion temperature (in the range 50-60 K, with about 1 W of cooling power needed to cool the gas flow). This allows to have a cooler efficiency of about 300 to 400 W of electrical power per W of cooling power at 20 K. A trade-off between active coolers (Stirling) and a radiator was made, leading to the selection of the radiator. The main reasons for this are that the telescope also needs also such a low temperature environment, that a 50-60 K radiator seems to be feasible in the L₂ orbit, and that the overall design is simpler. This 20 K cooler will be also the dominant power consumer of Planck (figure 4-2), and will drive the power budget, solar array, and SVM thermal control design.

The 20 K environment for LFI is also used to pre-cool the HFI cooling system. The coldest stage of HFI (0.1 K) is using open loop the dilution refrigerator designed by A. Benoit (10) at CRTBT. This cooler is similar in principle to the dilution refrigerator used in ground based low temperature laboratories, except that it runs in an open loop, both fluids are circulating, and the dilution effect takes place a capillary. ³He and ⁴He gas coming from high pressure storage tanks, are pre-cooled at various stages and then mixed to produce the required cooling at 0.1 K from the difference of enthalpy between the diluted and concentrated phases of ³He. The return line is used to pre-cool the injection line by recuperative heat exchange, and finally the mixture is released to space.

The dilution refrigerator requires the gas to be pre-cooled at a temperature lower than 10 K. This is performed by a closed cycle 4 K Joule Thomson (JT) Cooler using ⁴He as a fluid, and a pair of mechanical compressors. These compressors are similar to the qualified 50 K and 20 K Stirling coolers developed by MMS. They are mounted back to back, and controlled by a low vibration drive electronics with force transducers and a servo feedback loop to minimise the exported vibrations.

A development model of a complete 0.1 K Cooler compatible with a Space mission (11) using 20 K Stirling (8) and 4 K JT pre-coolers (9) (and no radiator) is under development at the Institut d'Astrophysique (IAS, Orsay-France) under ESA and CNES (French Space Agency) funding. From this set up, as the 20 K environment is already available from the LFI instrument, Planck will only use the 4 K pre-cooler and the dilution refrigerator.

The global architecture of the Planck cooling system is shown on figure 4-1. The 3 active coolers have their
source of compressed gas located on the SVM structure and radiators (Sorption compressor for the H₂ cooler, Mechanical compressor for the ⁴He JT Cooler, and high-pressure vessels and valves for the Dilution cooler). The link between these warm units and the cold finger is made via capillaries, with the injection line (high pressure) and return line (low pressure), which includes recuperative counter-flow heat exchangers, and thermal anchoring on the various shields.

**Planck Payload architecture and design.**

From the low temperature requirements of the instruments and telescope, and the selection of a passive pre-cooling, the architecture of the Planck payload is obvious (figure 4-3): the complete payload has to be equipped with a radiator, shielded from the sun radiation, and insulated from the warm parts, e.g. shield and SVM. In addition, the fact that Planck has to carry the 3 tons of the FIRST Satellite during launch gives additional constraints on the PPLM.

**Radiator Design**

While the low temperature coolers are being provided by the instruments, the 60 K pre-cooling stage for these coolers, for the telescope and to intercept the heat losses of all the connections (harness, support, wave guides) will be provided by the PPLM.

The design of the radiator itself is straightforward: a black painted aluminium honeycomb panel (emissivity > 0.9 over the 50 K to 300 K blackbody spectrum) with an area of about 3 m² is sufficient to evacuate 1 W at 50 K (figure 4-4). A thickness of 0.3 to 0.5 mm of both aluminium skins is sufficient to limit the temperature gradient to lower than 5 K between the hot spots (cooler heat exchangers) and the rest of the panel.

The ideal performances of the radiator are usually difficult to obtain. Typical degradation factor between 2 and 10 are common between actual performances of existing radiators and ideal radiators. The main reasons are the earth radiation, the actual emissivity, and non-perfect thermal insulation.

The earth radiation is negligible in the L₂ orbit. In addition, the earth is also shadowed by the sunshield.

The emissivity assumed for the design (0.9) is typical for black paint. Better emissivity (0.95) could be obtained by using the cavity effect of open honeycomb. It is to be noticed here that black paint used for the heat rejection of the radiator is almost perfectly reflective in the mm wavelength range. But this is still fine with the stray-light design, relying on reflective surfaces.

**Thermal Insulation of the Planck Payload**

The thermal insulation on the cold payload relies on two aspects: reducing the radiative and the conductive links.

To reduce the radiative links between the SVM and the PLM, we have analysed 2 types of solutions: the MLI...
Multi-Layer-Insulation), and the V-Groove shields\(^7,12\).

The MLI is the conventional approach, and is used in most of the existing passive cooler configuration such as Meteosat or IASI. Typical effective emissivity is of the order of 0.015, giving a heat flow of more than 6 W/m\(^2\) between 300 K and 50 K. This means that for a radiator providing 1 W cooling power at 50 K, a multi stage configuration is required. More, uncertainties on the MLI performances of a factor 2 or more are common (due to slits, holes, packing density, mounting, edge effects...). This usually results in a poor predictability for such designs, except if the radiation to space dominates the heat losses, which can be the case here.

The V-Groove concept is similar to the MLI in its principle, as it consist of several shields. But an open angle of few degrees between each shield giving each shield a view factor to space, allow an efficient heat rejection to space, resulting in excellent insulation efficiency. The radiation can escape easily from the shields, rather than being trapped as for the MLI. If \(\varepsilon\) is the emissivity of each layer, the equivalent emissivity of the V-groove shields assembly will be near \(\varepsilon^2\) compared to \(\varepsilon/n\) for a n-layer MLI. This becomes very efficient for very low emissivity, such as aluminium (\(\varepsilon=0.05\)) or gold (\(\varepsilon=0.02\)) coatings. In addition, the predictability of such a design with such shield is good, as the geometry and the coatings are well known. The drawbacks of the V-groove shields are the constraints on the geometry, and the integration.

The conductive links are the mechanical supports, the electrical cables and wave-guides, and the cooler pipes. The losses across the supports can be reduced using glass fibre (baseline) or alumina struts, and effective thermal anchoring on the intermediate stages. In addition, these struts shall be filled with foam to avoid radiative losses inside the struts. More, the effective heat transferred to the cold stage can be reduced by a factor 2 or 3 if we allow a view factor of these struts to space. The same principles apply for the cables, cooler pipes and wave-guides, except that a metallic material has to be selected. The cross sections must be minimised, and low conductive metal will be used: steel or brass for the cables (as for ISO), steel of CuNi for the cooler pipes, and steel with a thin gold layer for the wave guides.

**Planck Payload thermal configuration**

Figure 4-5 shows 3 possible configurations with the same Planck payload: configurations \(a\) and \(b\) are using a set of 3 conical V-groove shields, with a radiator on the last stage. Configuration \(c\) is based on the MLI concept, and a 2 stages radiator.

The difference between configuration \(a\) and \(b\) is the way to support the FIRST satellite during the launch. In configuration \(a\), which is the baseline, the cylinder which is used to carry FIRST is attached directly on the Planck SVM, limiting the size and the efficiency of the shields, as each shield has a view factor with the SVM. For that reason, configuration \(b\) has been proposed, where the interface ring to FIRST, and the Planck payload supports has been elevated between the 2\(^{\text{nd}}\) and the 3\(^{\text{rd}}\) shield, allowing a proper shielding effect.

**Thermal Analysis**

Simple thermal models of the Planck spacecraft (15-20 nodes) have been build, mainly to design the radiator and insulation. We use ESARAD for the calculation of the radiative exchange factors, and Microsoft Excel for the thermal model. It is going down to the 20 K stage of LFI represented as a boundary node, and uses a thermodynamic model of the 20 K cooler to estimate the dissipation due to enthalpy change at the various pre-

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![Figure 4-5: 3 possible payload architectures for Planck: a) with small V-Groove shields limited by the FIRST support interface on the SVM, b) with large shields and an elevated support interface, c) with MLI and a 2 stages radiator.](image-url)
cooling stages

The relevant temperature results for versions a, b, and c of figure 4-5 are shown in table 4-1.

Sensitivity of the baseline design (a) to uncertainty on input parameters is shown on table 4-2, showing a good predictability of this design, as the heat budget is dominated by radiation to space. The sensitivity is similar for the other configurations. The configuration c is dominated by the uncertainty on the MLI, but as stated earlier, the resulting error bar on the predicted temperatures in only ±4 K, as the radiation to space still dominates.

### 5: Development of the Spacecraft and the Payloads

The cryogenic systems of both Payload Modules, the FPLM and the PPLM are the most demanding elements of the spacecraft. An anticipated testing sequence of the modules with respect to their thermal cryogenic performance is outlined below.

**FIRST Payload Module - Cryostat Performance**

The cryostat performance of the FPLM is a key element of the orbital lifetime and the mission scenario. Therefore the lifetime of the cryostat should be verified on ground. The approach to this verification is a combination of two tests and thermal analysis. As a first step the Helium equilibrium mass flow under ground environmental conditions is measured (CVV at 293 K). A second test of the cryostat inside a LN$_2$ thermal vacuum test facility will provide the necessary characterisation of the system not too far from expected orbital condition (CVV at 90 K), and will also verify the transient behaviour of the cryostat after the launch. Aside the demonstration of the lifetime of the system, both tests will validate that the proper temperatures are achieved at the scientific instrument interfaces.

One of the ground tests is the demonstration of the capability of the system to support the ARIANE 5 launch sequence. This is a ground hold time of six days, where the main Helium tank is closed and in superfluid conditions and the thermal loads are kept low by Helium flow from the auxiliary Helium tank that boils off He at ambient pressure. The sequence foresees a refilling of this 80 litres tank every two days, the last two fills through dedicated doors in the launcher fairing.

The experience of ISO development will be an important issue to simplify the tests of the FIRST cryostat.

**Planck Payload Module - Development**

The demonstration of the performance of the cryogenic subsystem of the Planck Payload module is a major challenge. The performance depends on several interrelated items, each of which has to stay within its allocated performance range. The first step of the demonstration will be performed on a mechanical mock-up to optimise and verify the interfaces and the integration sequence. Due to the criticality of the module a two models philosophy is planned. The first hardware model, the qualification model, will be subjected to extended mechanical testing prior to thermal testing. The thermal test will consist of several steps and different test environments.

The first step will be the demonstration of the passive cooling concept, i.e. can the predicted temperature of around 60 K can be reached on the telescope and the optical bench. This demonstration calls for a very special thermal vacuum test with the facility being equipped with helium shrouds. The operation of the coolers, the 20 K

### Table 4-1: main temperature estimated for options a, b, and c.

<table>
<thead>
<tr>
<th>Option</th>
<th>Baseline, Adapter for SVM, 3 small V-Groove shields</th>
<th>Adapter above SVM, large V-Groove shields</th>
<th>2 stages radiator with MLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVM</td>
<td>293</td>
<td>293</td>
<td>293</td>
</tr>
<tr>
<td>Shield 1</td>
<td>169.7</td>
<td>145.1</td>
<td>81.7</td>
</tr>
<tr>
<td>Shield 2</td>
<td>104.6</td>
<td>89.8</td>
<td></td>
</tr>
<tr>
<td>Shield 3</td>
<td>55.8</td>
<td>52.0</td>
<td>59.3</td>
</tr>
<tr>
<td>LFI-HFI</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Primary Mirror</td>
<td>41.0</td>
<td>39.6</td>
<td>44.3</td>
</tr>
<tr>
<td>SVM Radiator</td>
<td>231.2</td>
<td>231.8</td>
<td>231.5</td>
</tr>
<tr>
<td>Solar array 2</td>
<td>344.9</td>
<td>361.1</td>
<td>344.9</td>
</tr>
</tbody>
</table>

### Table 4-2: Sensitivity of the design configuration (a) to uncertainties on parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Error x</th>
<th>Error</th>
<th>T Nominal</th>
<th>Delta T+</th>
<th>Delta T-</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLI Efficiency</td>
<td>0.015</td>
<td>100%</td>
<td>60%</td>
<td>55.8</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>2K cooler dissip</td>
<td>0.82 W</td>
<td>20%</td>
<td>20%</td>
<td>53.6</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>SVM Temperature</td>
<td>293 K</td>
<td>5%</td>
<td>-10%</td>
<td>55.9</td>
<td>0.83</td>
<td>-1.65</td>
</tr>
<tr>
<td>Glass Fiber Conductivity</td>
<td>1</td>
<td>20%</td>
<td>20%</td>
<td>55.8</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Steel conductivity</td>
<td>1</td>
<td>20%</td>
<td>20%</td>
<td>55.8</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Carbon Fibre conductivity</td>
<td>1</td>
<td>20%</td>
<td>20%</td>
<td>55.8</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Al Coating emissivity</td>
<td>0.05</td>
<td>40%</td>
<td>50%</td>
<td>58.7</td>
<td>1.17</td>
<td>1.45</td>
</tr>
<tr>
<td>Al Coating reflectivity</td>
<td>0.1</td>
<td>40%</td>
<td>50%</td>
<td>57.10</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>RSS</td>
<td></td>
<td></td>
<td></td>
<td>1.8</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>
sorption cooler for LFI, the 4 K and dilution cooler and the demonstration of adequate temperatures in the focal plane unit follow the first part of the thermal test. Beside low temperatures, Planck requires also extreme temperature stability, which should be achieved passively.

The instrument operation, i.e. detector operation, and the inter-compatibility of the two focal plane units will complete the cryogenic system qualification model test sequence. For this part of the test, the radiative cooling stage will have to be supported by ground support cooling equipment to reduce the time constants. On the flight model the above tests are repeated to such a level to verify proper operation of the payload module and the scientific payload.

6: Programmatic Status and Outlook

The above-described cryogenic design is a result of the system definition studies performed by ESA and the European industry in the period from summer 1997 to spring 1998. The "Carrier" configuration has been selected last May 1998, together with the provisional selection of the 5 instruments. The next step will be a detailed study of the Planck payload Module, finalisation of the instruments/spacecraft interfaces, and FIRST PLM delta studies as required. At the same time the instrument development has already started in the instrument consortia \(^{(1)}\). The beginning of phase B is expected to start early 2001, for a launch in 2007.

7: Acknowledgements

The spacecraft design as presented above is the result of the work performed by Aerospatiale-Cannes, Matra-Marconis Space-Toulouse, who performed the system feasibility studies and proposed the "Carrier" as a promising option, and Dornier-Satelliten-Systeme who worked on the FIRST PLM. We gratefully acknowledge their contributions. We would like to thank the FIRST / Planck Scientific community who defined the model payloads and is now involved in the instrument definition, and the ESA FIRST / Planck project team who carried out the Planck Carrier feasibility study.

8: References

1. http://astro.estec.esa.nl/First