The FIRST ESA Cornerstone Mission

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ABSTRACT

The 'Far InfraRed and Submillimetre Telescope', (FIRST), is the fourth European Space Agency (ESA) cornerstone mission (CS4) in the current 'Horizons 2000' science programme. FIRST will perform photometry and spectroscopy in approximately the 80−670 μm range in the far infrared and submillimetre part of the spectrum.

The key scientific topics to be addressed by FIRST will include subjects as diverse as how and when galaxies formed in the universe, interstellar medium physics and chemistry including large- and small-scale star formation – which in turn is linked to galaxy formation – in our own and external galaxies, and observations of solar system objects. In the course of recent years there has been a gradual shift in emphasis towards extragalactic astronomy.

FIRST will have a passively cooled 3.5 m diameter Cassegrain/Ritchey-Chrétien telescope, to be provided by NASA, and a science payload complement of three instruments, which will be provided by Principal Investigators (PIs) and their consortia. The focal plane units of these instruments will be housed inside the payload module which provides a cryogenically cooled environment using the superfluid helium cryostat technology developed for the successful ESA Infrared Space Observatory (ISO) mission.

It has been decided to perform a joint implementation of FIRST and the Planck cosmic microwave background mapping mission. The nature still has to be decided upon; the baseline being sharing a spacecraft facility – the 'merged' mission – with a Planck payload module containing the two Planck instruments and telescope to be accommodated under the FIRST service module. In this configuration the FIRST and Planck observations would be carried out consecutively and independently of each other.

Irrespectively of the details of the implementation – which have only minor implications for the FIRST payload module – FIRST has been conceived as a multi-user observatory. It will be open to the general astronomical community on the basis of calls for observing time proposals, and is scheduled to perform routine observations from year 2006, operating from an orbit around the L2 Lagrangian point in the Earth/Moon-Sun system about 1.5 million km away from the Earth.

Keywords: Space astronomy, galaxy formation, star formation, interstellar medium, far infrared, submillimetre, FIRST, Planck, cryogenic

1. INTRODUCTION

The 'Far InfraRed and Submillimetre Telescope' (FIRST) is a multi-user 'observatory type' mission that targets approximately the 80−670 μm wavelength range in the far infrared and submillimetre part of the electromagnetic spectrum. FIRST is one the original four 'cornerstone' missions in the European Space Agency (ESA) 'Horizon 2000' long term science plan[1]. It was selected for implementation as Cornerstone 4 (CS4) by the ESA Science Programme Committee (SPC) in its November 1993 meeting.

Descriptions of the scientific objectives, reference model payload, spacecraft and system design, and science operations and overall management for the mission as selected can be found in[2,3,4,5]. When selecting FIRST, the SPC also decided that definition work on all aspects of the mission should continue with the objective of firmly establishing a mission that can be implemented with low technical risk and cost. The SPC would then 'reconfirm' its decision at a later time. This process has naturally also included a constant (re-)assessment of the science objectives and model payload of FIRST. In the course of this process the baseline has become to implement FIRST using the well proven ISO cryostat technology with a model payload consisting of three instruments[6,7].

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In 1997 a number of similarities between the Planck cosmic microwave background mapping mission and FIRST prompted ESA to study the possibility of combining the two projects. The objective being to ascertain whether a technical solution exists which combines both missions without compromising their respective scientific capabilities, while giving rise to significant cost reductions. A range of possibilities have been considered in the context of these studies; one option being the use of a single launcher to put both spacecraft into orbit, another to use a single spacecraft with separate FIRST and Planck payload modules; the so-called 'merged' FIRST/Planck mission. In the meantime the Announcement of Opportunity (AO) for the science instruments for both FIRST and Planck has been issued. A final evaluation and decision on how to implement both missions, and the selection of their respective instruments, is scheduled to take place in spring 1998.

2. SCIENCE OBJECTIVES

The FIRST wavelength region of the spectrum, 80−670 μm, bridges the gap between what can be observed from current and future ground-based facilities and that of other space missions. Black-bodies with temperatures between 5 K and 50 K peak in the FIRST wavelength range, and gases with temperatures between 10 K and a few hundred K emit their brightest molecular and atomic emission lines here. Broadband thermal radiation from small dust grains is the most common continuum emission process in this band. These conditions are widespread everywhere from within our own solar system to the most distant reaches of the Universe!

The science objectives of FIRST have been constantly discussed and reviewed since first formulated, most notably in a number of major symposia, including in Segovia, 1986[8], in Liège, 1990[9], in a special 'hearing' organised by the FIRST Science Advisory Group (SAG) with invited experts in September 1996, and finally further elaborated upon in another major FIRST symposium which took place in April 1997 in Grenoble[10].

2.1. Predicted sensitivities

Observing time from a space platform is particularly precious. It is therefore necessary to ensure that the available FIRST time is allocated to areas where its capabilities are unique and its scientific impact will be the most profound. As a starting point in the 'hearing', the predicted sensitivity of the then current FIRST design and model payload (cf. Figure 1) was compared to foreseen complementary ground-, air-, and space-based observing facilities. From the predicted sensitivities it was concluded that:

- Progressing to shorter wavelengths there is a point somewhere in the 100−150 μm range where a smaller cryogenic telescope will be more sensitive, although FIRST may well have better angular resolution and lower confusion limits.

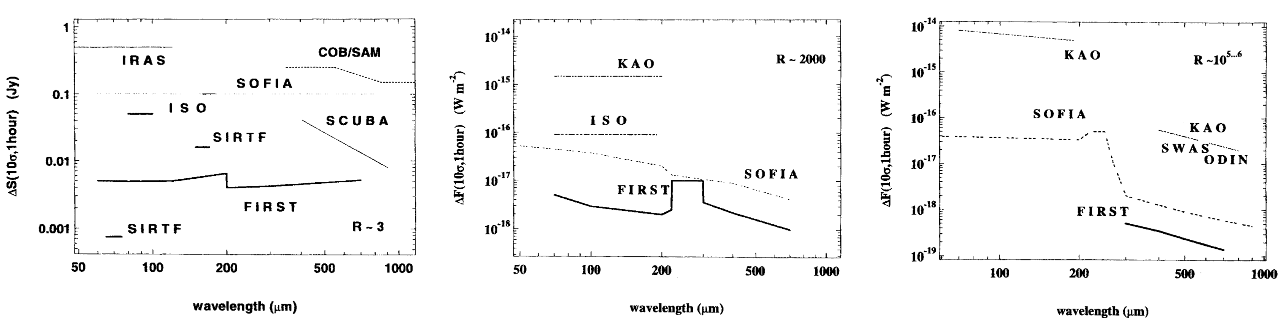


Figure 1. Calculated FIRST sensitivities (model payload) for (from left to right) photometry (R ∼ 3), medium (R ∼ 2000), and very high (R ∼ 10^{5-6}) resolution spectroscopy. Plotted are also actual or calculated sensitivities for a number of complementary facilities. Note that the curves are 10σ noise levels for 1 hour observations. From R. Genzel (private communication).

- Progressing to longer wavelengths there is a point somewhere in the 800−900 μm range where larger ground-based instruments will be more sensitive and have better angular resolution.

- The sensitivity advantage offered by the relatively cold and very low emissivity FIRST telescope in the space environment decreases for (very) high resolution spectroscopy.

The conclusion is that FIRST has unique capabilities in performing photometry and (medium) resolution spectroscopy in approximately the 100−600 μm range. In addition, from space FIRST has access to lines – for very high resolution spectroscopy – that cannot be reached at all from e.g. aircraft altitude.

2.2. Key science goals

The outcome of the assessment made by the 'hearing' was a list of key science objectives for FIRST that emphasises extragalactic astronomy, specifically the formation of galaxies, and star formation and how it relates to galaxy formation. The science objectives were further discussed in the Grenoble symposium[10,11]; the list includes (but is not necessarily limited to):

- Deep broadband photometric surveys in the 100−600 μm FIRST 'prime' wavelength band and related research. The main goals will be a detailed investigation of the formation and evolution of galaxy bulges and elliptical galaxies in the first third of the present age of the Universe.

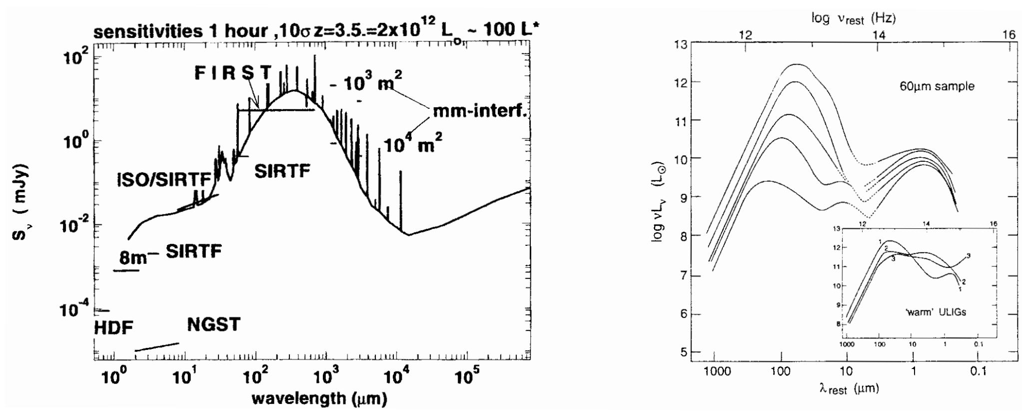


Figure 2. Left: Calculated 10σ 1 hour sensitivities (per detector) for detecting a 100 L* starburst galaxy at z = 3.5. From R. Genzel (private communication). Right: Spectral energy densities for a number of the IRAS 60 μm sample of galaxies. Ultraluminous IR galaxies emit 90−99 % of their bolometric luminosity in the IR. The optical/near-IR luminosity is a very poor indicator of bolometric luminosity. From Sanders & Mirabel, Ann. Rev. Astron. Astrophys. 1996, 34:749.

While optical/near-IR observations can detect the stellar light emerging from galaxies undergoing star-formation bursts out to very high redshifts (cf. Figure 2, left), they cannot unambiguously determine their total bolometric luminosity (i.e star-formation rate) since the fraction, depending on dust content, of reprocessed (into the IR) star-light is unknown (cf. Figure 2, right).

Gravitationally lensed ultra-luminous IR galaxies such as e.g. FSC 10214+4724[12,13] already prove the existence of dusty high redshift starburst galaxies, and the spatially integrated emission of a population of such galaxies may already have been detected[14,15]. Furthermore, the potential discovery of new classes of objects is an intriguing possibility.

- Follow-up spectroscopy of especially interesting programme objects discovered in the survey. The far infrared/submillimetre band contains the brightest cooling lines of interstellar gas, which give very important information on the physical processes and energy production mechanisms (e.g. AGN vs. star formation) in galaxies[16].

- Detailed studies of the physics and chemistry of the interstellar medium in galaxies, both locally in our own Galaxy, as well as in external galaxies, including objects at high redshift. This includes implicitly the important question of how stars form out of molecular clouds in various environments.

- Observational astrochemistry (of gas and dust) as a quantitative tool for understanding the stellar/interstellar lifecycle and investigating the physical and chemical processes involved in star formation and early stellar evolution in our own Galaxy. Virtually all major components of this lifecycle (e.g. cloud collapse, freeze out, disk formation, dust coagulation, and planetesimal formation (cf. Figure 3) can be probed with FIRST.

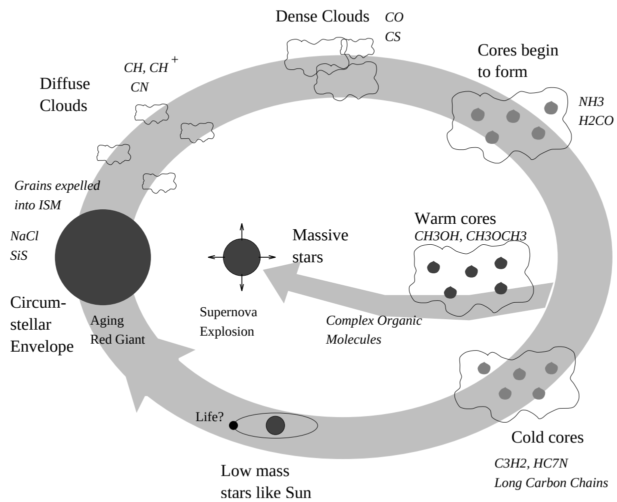


Figure 3. Schematic illustration of the processing of material in the interstellar medium. From van Dishoeck & Helmich, 1997, ESA SP–388, 3.

An important advantage of a space mission such as FIRST over ground-based or even airborne observatories is its complete spectral coverage over a wide wavelength range, unhindered by the atmosphere[17]. A thorough knowledge of these processes in our own Galaxy is a prerequisite for understanding galaxy- and star-formation at high redshifts.

- Detailed high resolution spectroscopy of a number of comets, high resolution molecular spectroscopy of the cool outer planets, and searches for Kuiper-belt objects.

From past experience, it is also clear that the 'discovery potential' is significant when a new capability is being exploited for the first time. Observations have never been performed in space in the 'prime band' of FIRST. As a space facility is essential in this wavelength range, FIRST will be breaking new ground!

3. PRESENT FIRST MISSION OPTIONS

3.1. Background

As described in section 1 the final decision on how to implement FIRST, although imminent, has yet to be taken. The mission selected for implementation as CS4, i.e. the concept in circa 1993 which was based on the outcome of an industrial study performed in 1992−93, envisaged a spacecraft with payload module having a telescope assembly with a 3 m diameter Cassegrain telescope radiatively cooled inside a sunshade, a science payload 4.5 K environment created by mechanical cryocoolers housing two science instruments, and were to operate from a highly eccentric (ISO-like) Earth orbit with a period of 24 hours.

Subsequent studies have shown that the now well proven ISO cryostat technology can be used to advantage also for FIRST, especially for orbits far away from the Earth, making it possible to accomodate a science payload complement of three instruments in a focal plane environment providing temperatures as low as the superfluid helium bath at 1.7 K. All presently studied FIRST configurations envisage a payload module based on ISO cryostat technology, and operation in the Lagrangian point L2 of the Earth/Moon−Sun system which is located approximately 1.5 million km away from the Earth.

3.2. Spacecraft concept

Three different possibilities for implementing FIRST (and Planck) are being considered[18]. They are the already mentioned 'merged' option, where the FIRST and Planck scientific missions are conducted consecutively and independently of each other using the same 'facility' consisting of FIRST and Planck payload modules (PLMs) sharing a common service module (SVM), the 'carrier' option in which FIRST is carried on top of Planck during the launch phase, and two 'stand-alone' completely separate missions.

The recent industrial studies have focussed on the 'merged' concept, which is technically the most challenging. However, from a FIRST point of view, the telescope and instrument accomodation, as well as the entire PLM configuration differ very little between the various options. The main difference is simply the cryostat lifetime which in the 'merged' configuration has to be sufficient for the total duration of both FIRST and Planck scientific operations. Two studies of the 'merged' mission have been performed competetively and in parallel by industry, one configuration (the main diffferences are in the Planck PLM which is outside the scope of the present paper) is shown in Figure 4.

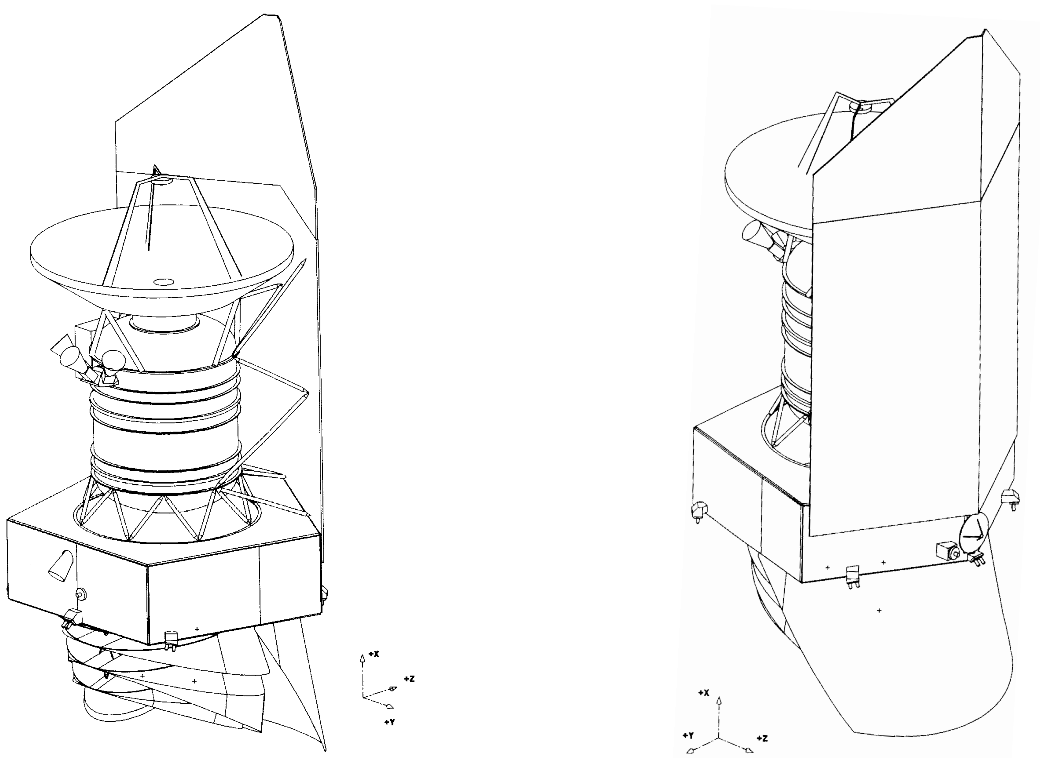
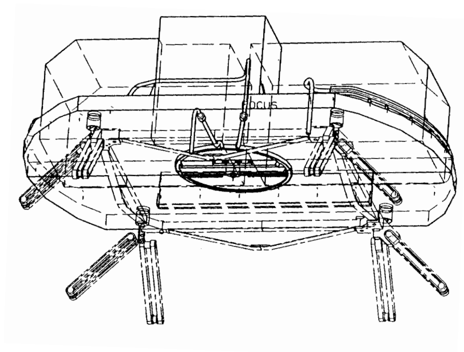


Figure 4. Two views of the 'merged' FIRST/Planck satellite. It measures approximately 11 m in height, 4.5 m in width, and has a launch mass of 4700 kg. The 3.5 m diameter FIRST telescope is protected by the sunshade, and will cool passively to below 80 K. The FIRST payload is housed inside the cryostat, which contains 2560 l of superfluid helium at 1.7 K giving a predicted cryostat lifetime of 4.5 years in the L2 orbit. The fixed solar panels, three startrackers in a skewed configuration, and the local oscillator unit for the heterodyne instrument are visible on the outside of the cryostat vacuum vessel. At the bottom the Planck payload module. Sun is in the +z direction.

The cryostat employs three vapour cooled shields with multi-layer insulation (MLI). It has a segmented superfluid helium tank, with a capacity of 2560 l, and an auxiliary 79 l helium tank for launch autonomy. The tank suspension design is similar to that of ISO. The anti-sunward side of the cryostat vacuum vessel (CVV) is used as a radiator, made possible by operation in orbit around L2. This lowers the CVV temperature significantly as compared to the situation in an eccentric Earth orbit.

The focal plane units of the science payload instruments are mounted on a honeycomb optical bench with carbon-fibre-compound (CFC) facesheets, as shown in Figure 5, and have a common instrument protection shield. The predicted temperatures for various cryostat levels are also given in the table in Figure 5. The 1.7 K level is obtained by use of a silver strap from each instrument that is in direct contact with the cryogen, the 4 K level by copper straps from each instrument connected to the wheel-shaped heat exchanger, while the '15 K' level is gas cooled. The predicted stationary helium massflow rate during routine FIRST science operations is 2 mg s^{-1}, which is equivalent to 63 kg (or 435 l) per year.



Item:	temperature (average mode)
Instrument cold stage	1.7 K
\`4,3K-level´	4.0 K
\`15K-level´	9.0 K
Optical Bench	11.7 K
Common Instrument Shield	12 K
Heatshield 1	30 K
Heatshield 2	43 K
Heatshield 3	62 K
CVV average	77 K
Telescope	78 K

Figure 5. At left the focal plane optical bench with the wheel-shaped heat exchanger, the instrument connections at the 4 K level are indicated. The eight supports to the CVV are also shown, while the common instrument shield is not. At right a table of predicted temperatures appropriate for FIRST routine science operations far away from the Earth.

3.3. Telescope development

The FIRST telescope will be provided by NASA/Jet Propulsion Laboratory (JPL) as part of NASA's involvement in the FIRST mission. The telescope will have a Cassegrain (or Ritchey-Chrétien) design with a 3.5 m diameter primary and an 'undersized' secondary. It shall have a total wavefront error (WFE) of less than 10 μm (with a goal of 6 μm) – corresponding to 'diffraction-limited' operation at 150 μm (goal 90 μm) – in orbit, and a very low emissivity. Being protected by a fixed sunshade, it will radiatively cool to an operational temperature of below 80 K in the L2 orbit. The baseline is an all carbon fibre reinforced plastic (CFRP) telescope, the manufacture of which is a very complex process, demanding precise control of a large number of parameters and skilled workmanship. JPL is currently in an evalution phase, and is also trading off possible alternatives.

3.4. Launch and operations

FIRST/planck would be launched directly into an L2 orbit transfer trajectory by a dedicated Ariane 5. About half the year has reasonable daily launch windows with acceptable L2 orbit injection Δv. For a stand-alone FIRST the launch window is open throughout the year – except for a two week period around each of the two equinoxes and a couple of days per month (to avoid the Moon). In both cases an eclipse-free orbit for the entire mission duration can be selected, or obtained by the use of an eclipse avoidance manoeuver[19].

Allowing for initial cool-down and subsequent operations far away from the Earth, the superfluid liquid helium cryostat, providing focal plane science instrument cooling, has a calculated lifetime in excess of 4.5 years using the instrument parameters of the 'model payload' used in the course ofthe industrial work. For the 'merged' FIRST/Planck mission the operations of FIRST and Planck science payloads will take place independently and consecutively according to scheme which ensures early results from some FIRST 'key projects' (cf. section 5) as well as completion of the full Planck mission in the course of the first two years of science operations. A possible sequence of in-orbit operations could look like:

Satellite commissioning	1 month
Performance verification	2 months
Science demonstration	1 month
FIRST observations	3 months
Planck full sky survey	7 months

FIRST observations	5 months
Planck full sky survey	7 months
FIRST observations until boil-off	$\geq$ 28 months

Planck routine observations cannot commence until the orbit around L2 has been reached after around 6 months, however, the time in transit can be used by FIRST. A full Planck survey takes approximately 6.5 months, there is also two weeks allocated at the beginning of each survey for preparations and performance verifcation. In the case of separate FIRST and Planck spacecraft obviously there will be no gaps in the FIRST schedule for Planck operations.

FIRST scientific operations are planned to be conducted 20−22 hours per day, while (the remaining) 2−4 hours per day are allocated for data downlink by repointing the spacecraft to the Earth and using the 32 m antenna of the ESA groundstation in Perth, Australia. The science operations will be conducted using a 'decentralised' ground segment concept that is further described in section 6.

4. SCIENCE PAYLOAD

4.1. Model payload

In the course of the spacecraft definition activities the industrial contractors have used a 'model payload' as defined by the FIRST Payload Working Group (PWG). It has been used to assess the scientific capabilites of FIRST, and to to assess payload accomodation, to identify the areas where the payload is critically driving the spacecraft design, and to define interfaces and requirements for payload and spacecraft. This 'model payload' consisted of three instruments: a bolometer, a photoconductor, and a heterodyne instrument, normally referred to as the BOL, PHOC, and HET.

The actual FIRST science payload will be provided by Principal Investigator (PI) consortia, which will be selected through an Announcement of Opportunity (AO) process. The AO process is ongoing, the deadline for submission of proposals was 16 February 1998. In response to the AO ESA has received three proposals:

- The Heterodyne Instrument for FIRST (HIFI) instrument is proposed by a consortium led by Th. de Graauw, SRON, Groningen, The Netherlands,
- The Photoconductor Array Camera and Spectrometer (PACS) instrument is proposed by a consortium led by A. Poglitsch, MPE, Garching, Germany.
- The Spectral and Photometric Imaging REceiver (SPIRE) instrument is proposed by a consortium led by M. Griffin, QMW, London, UK.

4.2. HIFI: a heterodyne receiver instrument

The proposed HIFI instrument[20] combines the high spectral resolving power capability of the radio heterodyne technique with the low noise detection offered by superconductor physics. It employs five pairs of Superconductor-Insulator-Superconductor (SIS) mixers giving continuous frequency coverage of the 480−1250 GHz band, while a sixth band will provide coverage for the 1410−1910 and 2400−2700 GHz band using Hot Electron Bolometer (HEB) mixers. An instantaneous bandwidth of 4 GHz analysed in parallel by a combination of wide- and narrow-band spectrometers will enable HIFI to perform rapid and complete spectral surveys with resolving powers R ($=\lambda/\delta\lambda$) in the range 10^3 to 10^7 (providing velocity resolution Δv in the range 0.03−300 km s^{-1}). The SIS mixers operate at 2 K level, being connected to the superfluid helium by straps. The HEB mixers require cooling to 0.5 K which is provided by a closed cycle ^{3}He adsorption cooler, which rejects heat to the 2 K level.

4.3. PACS: a photoconductor detector array instrument

The proposed PACS instrument[21] employs two 25×16 Ge:Ga detector arrays covering the two bands 80−130 μm and 130−210 μm. The short-wavelength band array is unstressed, while the long-wavelength one is stressed. The use of a dichroic beamsplitter and separate re-imaging optics for the two bands enables PACS to perform photometry simultaneously in the two bands, covering $\sim 1.5'\times1'$ and $\sim 3'\times2'$ on the sky, while providing full beam sampling at 90 μm and 180 μm, respectively. As a spectrometer PACS provides a resolving power R in the range 1500−2000 (Δv in the range 150−200 km s^{-1}) with an instaneous coverage of $\sim$ 1500 km s^{-1} and simultaneous imaging of a $\sim 50''\times50''$ field of view, resolved into 5×5 pixels. The photoconductor arrays operate at helium bath temperature and are read out by cryogenic readout electronics (CRE) operating at the 4 K level.

4.4. SPIRE: a bolometer detector array instrument

The proposed SPIRE instrument[22] comprises an imaging photometer and an imaging Fourier Transform Spectrometer (FTS). The photometer has three imaging arrays of bolometric detectors providing broadband photometry (R ~ 3) simultaneously in bands centred on 250, 350, and 500 μm using fixed dichroic beam-splitters. The FTS uses a Martin-Puplett polarising design with two input and two output ports. The two input ports view the sky and a calibration source, while in each of the two output ports there is an bolometer array, covering $200-300$ μm and $300-670$ μm respectively. The operating temperature of all detectors is 0.3 K, which is provided by a closed cycle ^{3}He sorption cooler. Several different kinds of detector arrays and and associated cold multiplexers are currently being considered for use by SPIRE; the best has yet to be selected.

4.5. Instrument selection

These proposed instrument proposals are now being assessed by external panels supported by ESA working groups, with the objective to have selection of instrument configurations and PIs for FIRST (and Planck) to be made by the SPC in the end of May 1998.

5. OBSERVATION PROGRAMMES

The FIRST observation time will be shared between guaranteed and open time. The guaranteed time will be implemented in the form of a 'core programme' defined by the guaranteed time holders. The open time will be allocated to the general community on the basis of calls for observing proposals. The split between guaranteed and open time is described in the FIRST Science Management Plan (which has been approved by the SPC) as follows:

Satellite commissioning	no observations
Performance verification	no open time
Initial 9 months	36 % open time
Following 12 months	64 % open time
Remaining time	76 % open time

The guaranteed time will be shared between the three the PI consortia (30 % each), the Mission Scientists (3 % combined), with the remaining time (7 %) belonging to the FIRST Science Centre staff. A small fraction (no more than 4 %) of the open time will be allocated to discretionary time and targets of opportunity.

Given the science objectives of the FIRST mission it is clear that key projects in the form of large spatial and spectral surveys will constitute very important elements of the observing programme, requiring a substantial fraction of the available time of the overall mission. It is envisaged that early in the mission a significant time will be spent on several key programmes, including spatial photometric surveys with additional time devoted to spectral surveys of selected key sources. The formation of large observer collaborations collectively addressing key topics will be actively encouraged. It is foreseen that there will be a separate initial call for observing proposals for key programmes and surveys only at an early stage. Only when these programmes have been established will the first call for 'normal' observing proposals be issued.

All proposals will be evaluated and graded by the FIRST Observing Time Allocation Committee (FOTAC) on the basis of scientific merit and technical feasibility. All scientific data will be archived and made available to the general astronomical community after the proprietary period of time has elapsed.

6. SCIENCE OPERATIONS

The scientific operations of FIRST will be conducted in a novel 'decentralised' manner. The proposed ground segment concept comprises five elements:

- a FIRST Science Centre (FSC), provided by ESA,
- three dedicated Instrument Control Centres (ICCs), one for each instrument, provided by their PIs,
- a Mission Operations Centre (MOC), provided by ESA.

The ground segment elements will be united by dedicated computer links into a coherent science ground segment. These computer links are part of the FIRST Integrated Network and Data Archive System (FINDAS) for which the FSC is responsible. The FSC acts as the single-point interface to the science community and outside world in general. Each ICC will be responsible for the operation of its instrument, and also for the provision of calibration and data reduction tools for all data generated. The execution of all in-orbit operations will be the responsibility of the MOC. The responsibility for the design, implementation, and operation of the MOC rests with ESOC. The FIRST Ground Segment Advisory Group (FGSAG) will consist of representatives of all ground segments elements. It monitors the progress of the development of the ground segment elements, their operation, as well as providing analysis on system level in view of the overall mission and science ground segment objectives, and provides advice.

All scientific data will be archived and made available through FINDAS, together with software tools to produce 'standard' data products and to further process the data interactively. The 'end product' of the mission will be derived in the post-operational phase and will consist of:

- the 'raw' data products and the 'final' software tools
- data reduced with the 'final' software tools to 'final standard' data products
- various documentation and manuals

The resulting 'historical' archive will be maintained 'indefinitely' by ESA, and will provide access to FIRST data for the benefit for the whole science community.

7. STATUS AND FUTURE SCHEDULE

FIRST and Planck are presently in a pre-phase B development phase. The technical studies which will provide the foundation for technical, financial, and programmatical trade-offs have been completed as of February 1998. Financial and programmatical information is being provided. In the meantime the instrument proposals for the FIRST and Planck instruments have been received, and the evaluation is about to start. These instrument proposals have been written assuming the 'merged' FIRST/Planck implementation is selected, with a schedule leading to a launch before the end of year 2005.

The selection of how to implement FIRST and Planck ('merger', 'carrier', or 'stand-alone' concept), as well as a pre-selection of the PIs and the science instruments is scheduled to be taken by the SPC in their meeting in end of May 1998. Subject to changes in the assumptions that the PI consortia were asked to make when providing their proposals – which could result from the SPC meeting if e.g. a different schedule or mission implementation were to be selected – and the resulting updates to the proposals, the pre-selection of the PIs and the science instruments will then be confirmed in a subsequent SPC meeting.

Current information can be found on the ESA Astrophysics FIRST (Planck) World Wide Web site at URL: `http://astro.estec.esa.nl/First (Planck)` .

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the work and dedication of a large number of individuals in- and outside ESA, and by the FIRST industrial contractors. The FIRST SAG is chaired by R. Genzel and includes P. Encrenaz, R. Hills, T. de Jong, E. Kollberg, J. Martin-Pintado, and G. Tofani; the FIRST PWG is chaired by P. Encrenaz and includes M. Griffin, J.-M. Lamarre, D. Lemke, A. Poglitsch, H. van de Stadt, and N. Whyborn. In addition, M. Rowan-Robinson and E. van Dishoeck have made important contributions.

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