The ESA FIRST cornerstone mission

Göran L. Pilbratt

ESA Astrophysics Division, Space Science Department, ESTEC / SCI-SA, Keplerlaan 1,
NL-2201 AZ Noordwijk, The Netherlands

ABSTRACT

FIRST, the 'Far InfraRed and Submillimetre Telescope', is the fourth cornerstone mission in the European Space Agency (ESA) science programme. It will perform photometry and spectroscopy in the far infrared and submillimetre part of the spectrum, covering approximately the 60−670 μm range.

FIRST will carry a 3.5 metre diameter passively cooled telescope (to be supplied by NASA/JPL), and house a science payload complement (to be supplied by instrument consortia) of two cameras/medium resolution spectrometers (PACS and SPIRE) and a very high resolution heterodyne spectrometer (HIFI) in a superfluid helium cryostat. FIRST will be placed in a transfer trajectory towards its operational orbit around the Earth-Sun L2 point by an Ariane 5 (shared with Planck) in early 2007. Once operational FIRST will offer a minimum of 3 years of routine observations; roughly 2/3 of the available observing time is open to the general astronomical community through a standard competitive proposal procedure.

Keywords: Space vehicles: instrumentation; Stars: early-type, formation, late-type, pre-main sequence, winds, outflows; ISM: jets and outflows, molecules; Galaxies: evolution, formation, ISM; Infrared: galaxies, stars; Submillimetre

1. INTRODUCTION

The 'Far InfraRed and Submillimetre Telescope' (FIRST) is a multi-user 'observatory type' mission that targets approximately the 60−670 μm wavelength range in the far infrared and submillimetre part of the electromagnetic spectrum, providing observation opportunities for the entire astronomical community. FIRST is one of the original four 'cornerstone' missions in the ESA science 'Horizon 2000' plan; it was selected Cornerstone 4 in November 1993 by the ESA Science Programme Committee (SPC). It will be implemented in collaboration with NASA, and together with the instrument consortia.

FIRST is the the only space facility (see Figure 1) dedicated to the submillimetre and far infrared part of the spectrum. Its vantage point in space provides several decisive advantages. The telescope can be passively cooled to an operational temperature of about 80 K, which together with a low emissivity and the total absence of (even residual) atmospheric emission offers a very low and stable background that enables very sensitive photometric observations. Furthermore, the absence of atmospheric absorption gives full access to the entire range of this elusive part of the spectrum, which offers the capability to perform completely uninterrupted spectral surveys.

2. SCIENCE OBJECTIVES

The FIRST science objectives have been reviewed and have evolved since first formulated (see also[1,2]). They target the 'cold' universe; 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!

FIRST – being a unique facility in many ways – has the potential of discovering the earliest epoch proto-galaxies, revealing the cosmologically evolving AGN-starburst symbiosis, and unraveling the mechanisms involved in the formation of stars and planetary system bodies. The key science objectives emphasise specifically the formation of stars and galaxies, and the interrelation between the two. Example observing programmes with FIRST will include:

The author is the FIRST Project Scientist; email: gpilbratt@astro.estec.esa.nl, phone/fax: +31 71 565 3621/4690.

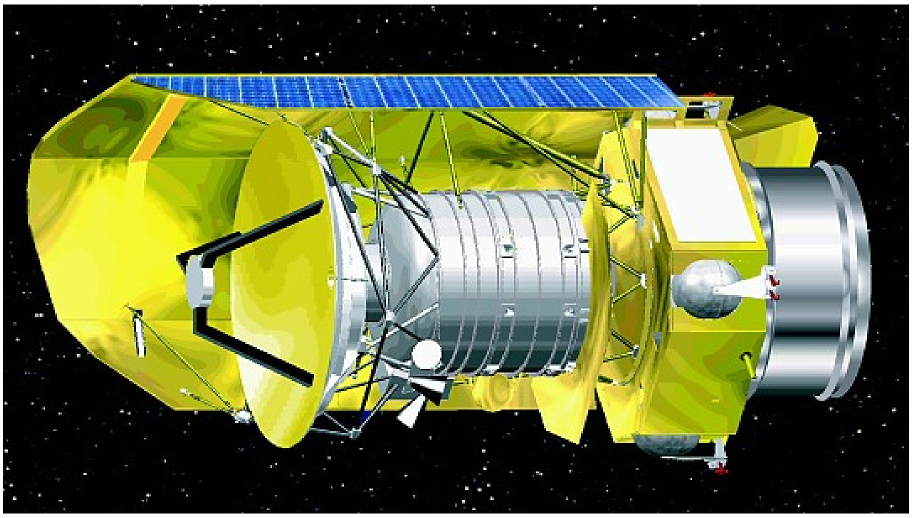

Figure 1. An artist's impression of a FIRST design (with payload module based on the ISO cryostat) in space. The approximate dimensions are: height 9 m, width 4.5 m, and launch mass 3200 kg; see Section 4.

- Deep extragalactic broadband photometric surveys (see Figures 2 and 3) 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.
- Follow-up spectroscopy of especially interesting 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.
- 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, by means of photometric and spectroscopic surveys and detailed observations. This includes implicitly the important question of how stars form out of molecular clouds in various environments.

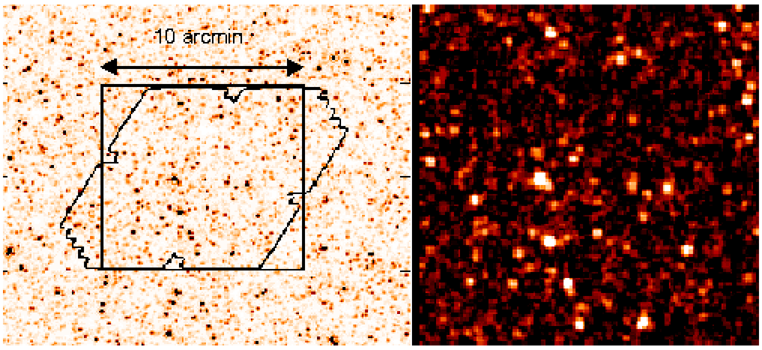

Figure 2. Simulations are underway to determine optimum instrument configurations and observation strategies for e.g. unbiased deep extragalactic surveys. On the left a model sky with observing pattern on the right and simulated SPIRE 250 μm data.

- 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. FIRST will provide unique information on most phases of this lifecycle.

- Detailed high resolution spectroscopy of a number of comets and the atmospheres of the cool outer planets and their satellites.

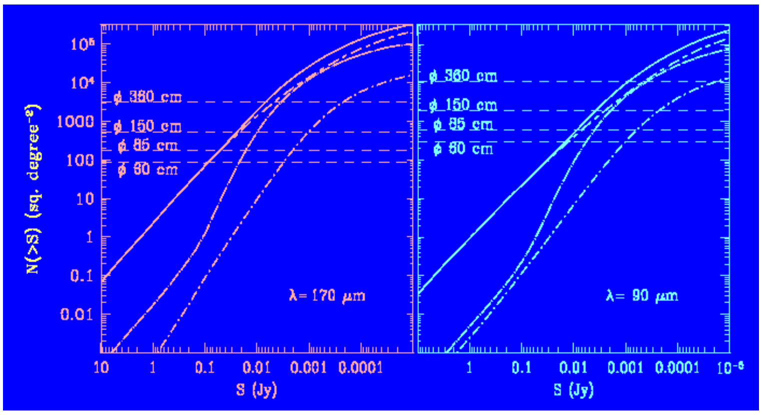

Figure 3. The large FIRST telescope will provide higher angular resolution and push the confusion limit down considerably compared to smaller cryogenically cooled telescopes. Shown are calculations (from Franceschini et al.) for PACS operating at 170 μm (left) and at 90 μm (right); the details depend on the assumed source distribution.

All astronomy missions and observatories – ground, air, and space based – to varying degrees rely on, and complement, each other; in this respect FIRST is not an exception. A major strength of FIRST is its photometric mapping capability for performing unbiased surveys related to galaxy and star formation. Redshifted ultraluminous IRAS galaxies (that 'peak' in the 50–100 μm range in their rest frames) as well as class 0 protostars peak in the FIRST 'prime' band; see Figure 4. FIRST is also well equipped to perform spectroscopic follow-up observations to further characterise interesting survey objects.

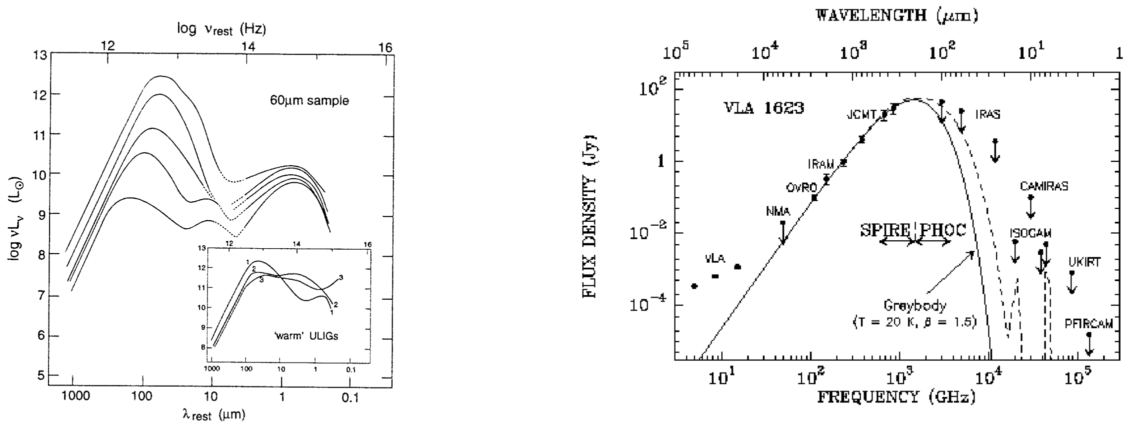

Figure 4. The FIRST wavelength coverage is ideally suited to for observing redshifted luminous IRAS galaxies (left) and class 0 protostars (right). Observations with PACS and/or SPIRE will enable the bolometric luminosity of such objects to be determined, which is not possible by observing e.g. in the near infrared or submillimetre only.

From past experience, it is also clear that the 'discovery potential' is significant when a new capability is being implemented for the first time. Observations have never been performed in space in the 'prime band' of FIRST. The total absence of (even residual) atmospheric effects – enabling both a much lower background for photometry and full wavelength coverage for spectroscopy – and a cool low emissivity telescope open up a new part of the phase-space of observations. Thus, a space facility is essential in this wavelength range and FIRST will be breaking new ground!

3. TELESCOPE AND SCIENCE PAYLOAD

In order to fully exploit the favourable conditions offered by being in space FIRST will need a precise, stable, very low background telescope, and a complement of very sensitive scientific instruments. The FIRST telescope will be passively cooled – to maximise size – while the instruments will be housed inside a superfluid helium cryostat.

3.1. Telescope development

The FIRST telescope will be provided by NASA/Jet Propulsion Laboratory (JPL) as part of NASA's involvement in the FIRST mission. It must 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 around 80 K in orbit.

The baseline is a Ritchey-Chrétien design with a 3.5 m diameter primary and an 'undersized' secondary. The telescope has a segmented primary mirror made of carbon fibre reinforced plastic (CFRP) structure, with a zerodur secondary that could be precisely machined to correct for low spatial frequency imperfections in the primary. An aggressive development programme is underway[3] to optimise the design – including optical, mechanical, thermal, and straylight properties – perfect manufacturing and testing procedures, and control potential detrimental environmental impacts.

3.2. Scientific instruments

The FIRST science payload has been conceived and optimised with the prime science goals in mind, but in addition it offers a wide range of capabilities for the 'general' observer. It was selected on the basis of the response to an Announcement of Opportunity (AO) issued in October 1997. The proposals received were reviewed favourably by an appointed committee of external scientists.

The Principal Investigators (PIs) and the instruments selected were:

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

The PI consortia provide the instruments to ESA under their own funding, in return for guaranteed observing time. The scientific payload complement was selected by the ESA Science Programme Committee in May 1998 and approved in February 1999.

3.2.1. PACS

PACS[4] is a photoconductor detector array camera and spectrometer instrument. It employs two 25×16 Ge:Ga detector arrays (see Figure 5) together covering the $60-210$ μm band. The two arrays are appropriately stressed and operated at slightly different temperatures – cooled by being 'strapped' to the liquid helium – in order to optimise sensitivity for their respective wavelength coverage. The stress mechanism is pictured in Figures 5 and 6.

PACS has three defined photometric bands with $R\sim2$. The short wavelength 'blue' array covers the $60-90$ and $90-130$ μm bands, while the 'red' array covers the $130-210$ μm band. The pixel sizes of the two arrays ($3.4''$ and $6.8''$, respectively) have been chosen to provide full sampling of the telescope point spread function at 90 and 180 μm. In the photometry mode PACS will perform imaging simultaneously in two bands, one of the 'blue' bands as well as the 'red' band, covering roughly $1'\times 1.5'$ and $2'\times 3'$ on the sky respectively.

As a spectrometer PACS covers 57–210 μm in three contiguous bands. It provides a velocity resolution in the range $150-200$ km^{-1} with an instantaneous coverage of ~1500 km^{-1}, and 25 pixels on the sky approximately covering $1'\times 1'$.

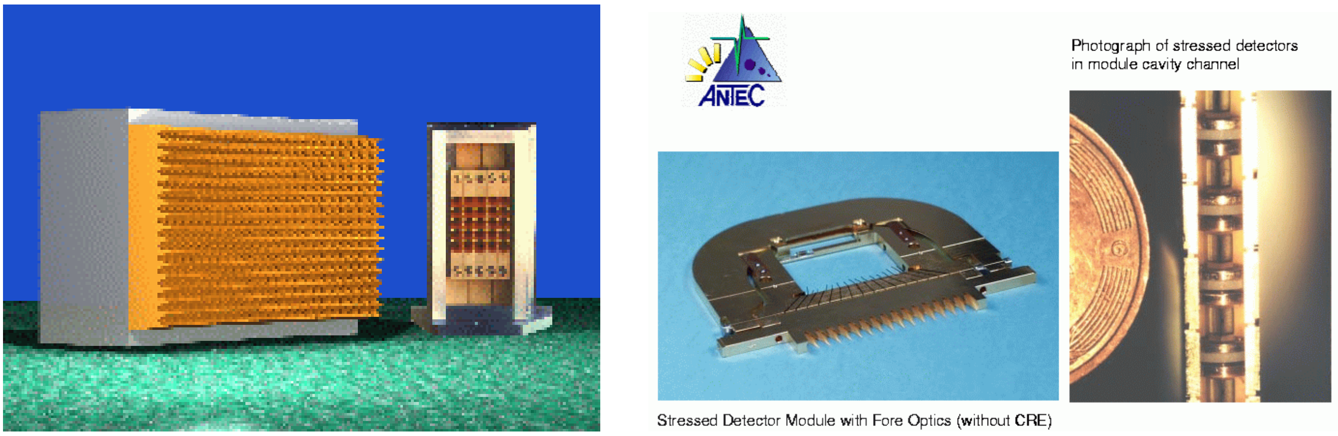

Figure 5. On the left a computer rendering of a PACS 25×16 array compared with the 5×5 Kuiper FIFI array; on the right pictures of the stress module (for a 1×16 linear array) with fore optics, and a close-up on a few individual detectors.

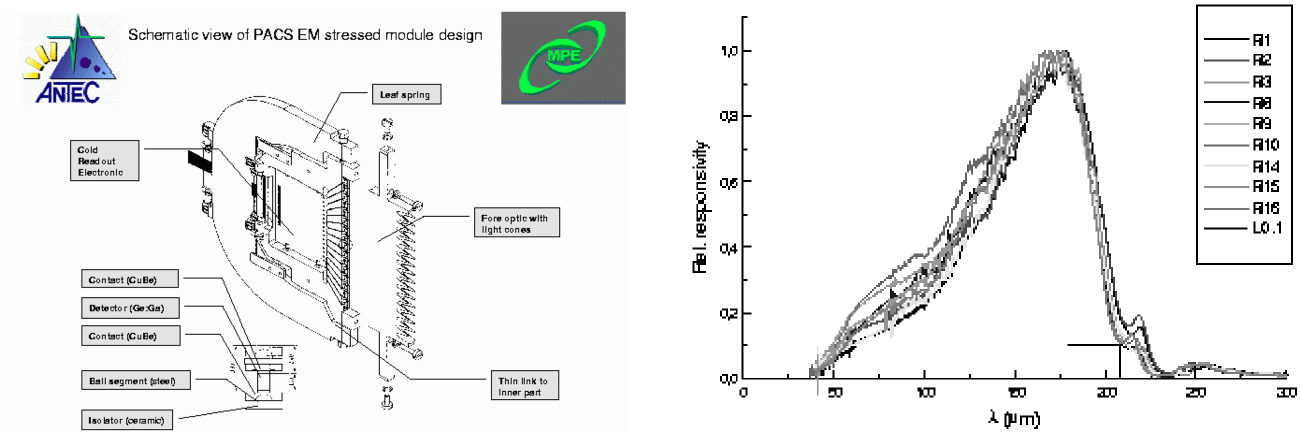

Figure 6. On the left a drawing detailing the stress module, a complete array is made up of 25 such modules. On the right the responsivity as a function of wavelength for a number of detectors verifying the uniformity of stress applied.

3.2.2. SPIRE

SPIRE[5] is a bolometer detector array camera comprising an imaging photometer and a symmetrical Mach-Zender imaging spectrometer. SPIRE has been designed to maximise mapping speed. In its broadband ($R \sim 3$) photometry mode it simultaneously images a $4' \times 4'$ (possibly even $4' \times 8'$) field on the sky in three colours centred on 250, 350, and 500 μm. The exact band centres are still subject to fine tuning.

Three detector technologies were being considered until recently for SPIRE. The CEA-SAp/LIR proposal utilised silicon grids with resonant absorbers and ion implanted thermometer readouts with CMOS cryogenic readout electronics and multiplexers. The NASA-GSFC/NIST array technology employed silicon 'pop-up' detectors (SPUDs) and transition edge superconductor (TES) sensors, with squid readouts and multiplexers.

The selected alternative is similar to the one currently used by the balloon-borne BOLOCAM instrument, and has similarities with the SCUBA instrument on the JCMT. It employs spider-web bolometers with NTD Ge temperature sensors, with each pixel being fed by a single-mode 2Fλ feedhorn, and JFET readout electronics operating at around

100 K. The three photometer arrays have a total of 288 detectors, the spectrometer 56. Since the telescope beam is not instantaneously fully sampled, it will be required either to scan along a preferred angle, or to ‘fill in’ by ‘jiggling’ with the internal beam steering mirror (see Figure 8).

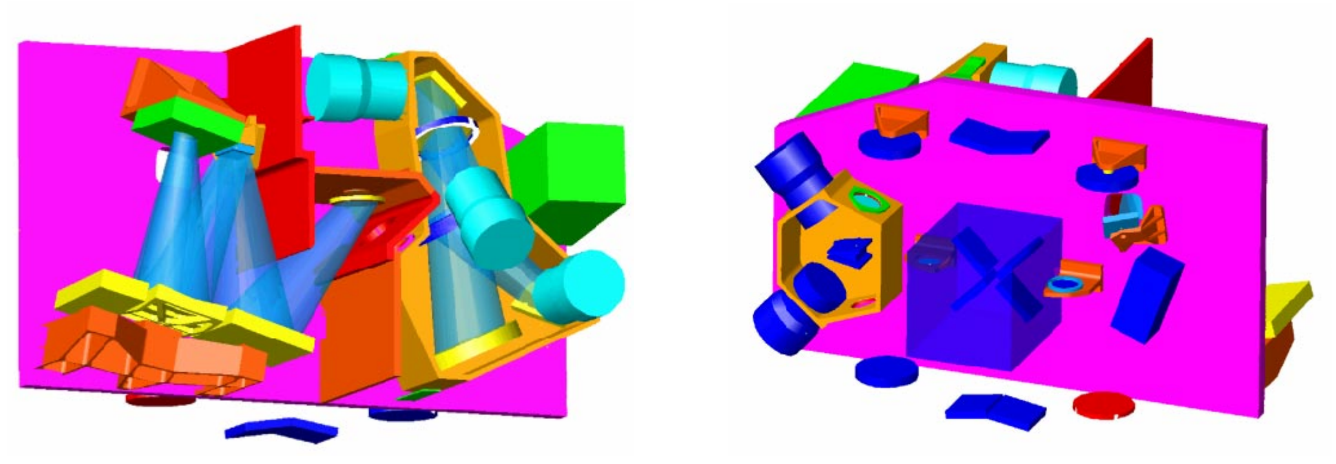

Figure 7. The SPIRE instrument has a photometer (left) and spectrometer (right) side, supported by a central ‘spine’. The photometer has three bolometer arrays that can be seen towards the right, while the spectrometer has two bolometer arrays on the other side of the ‘spine’. All five detector arrays are situated close to the internal ^{3}He sorption cooler which provides the 300 mK operating temperature.

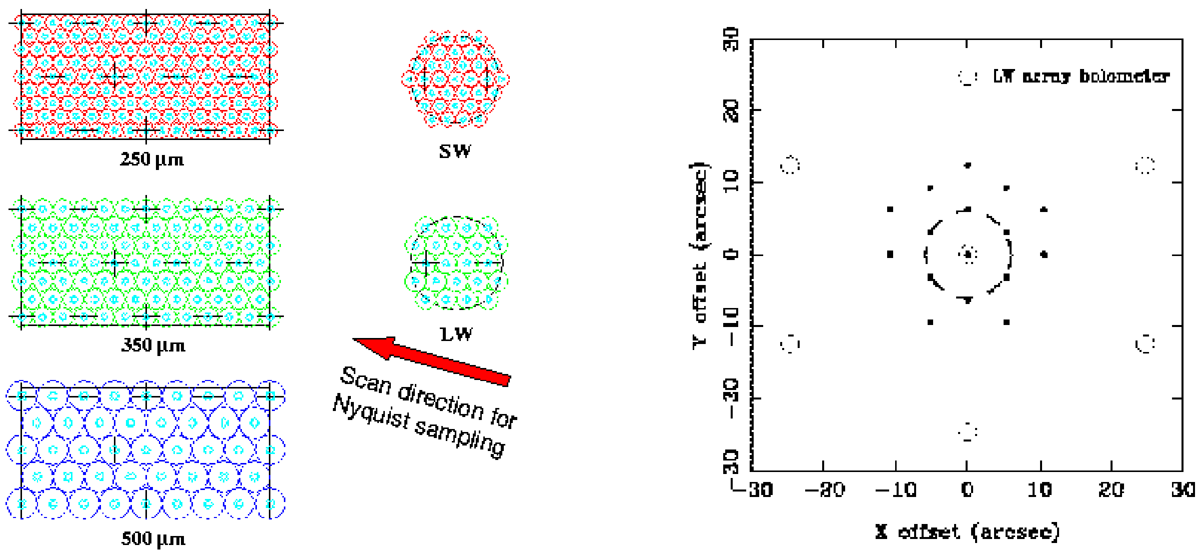

Figure 8. Since the SPIRE bolometer arrays do not fully sample the telescope beam in the focal plane, it is necessay either to scan (left) at a well defined angle (14.5° wrt to the ‘long’ array side) and map ‘on-the-fly’. Alternatively the ‘jiggling’ (right) method could be performed to ‘fill in’ the sparsely sampled map produced by the feedhorn detector technology.

The SPIRE spectrometer is based on a Mach-Zender configuration with novel broad-band beam dividers. Both input ports are used at all times, the signal port accepts the beam from the telescope while the second port accepts a signal from a calibration source, the level of which is chosen to balance the power from the telescope in the signal beam. The two output ports have detector arrays dedicated for 200−300 and 300−600 μm respectively. The maximum resolution will be in the range 100−1000 at a wavelength of 250 μm, and the field of view 2.6$'$ (square or circular).

3.2.3. HIFI

HIFI[6] is a heterodyne receiver instrument which combines the high spectral resolving power capability (0.3−300 km^{-1}) of the radio heterodyne technique with the low noise detection offered by superconductor-insulator-superconductor (SIS) and hot electron bolometer (HEB) mixers.

The focal plane unit (FPU, see Figure 9), houses seven mixer assemblies, each one equipped with two orthogonally polarised mixers. Bands 1−5 utilise SIS mixers that together cover approximately 500−1250 GHz without any gaps in the frequency coverage. Bands 6 and 7 utilise HEB mixers, and target the 1410−1910 and 2400−2700 GHz bands, respectively. The FPU also houses the optics that feeds the mixers the signal from the telescope and combines it with the appropriate local oscillator (LO) signal, as well as provides a chopper and the capability to view internal calibration loads.

The LO signal is generated by a source unit located in the spacecraft service module (SVM, see Section 4). By means of waveguides it is fed to the LO unit, located on the outside of the cryostat vessel, where it is amplified, multiplied and subsequently quasioptically fed to the FPU. The SVM also houses the wideband acoustoptic spectrometers and the high resolution digital autocorrelators.

HIFI is not an imaging instrument, it provides one pixel on the sky, but has very high frequency multiplexing. Imaging with HIFI is performed by raster mapping or by continuous slow scanning while observing, often referred to as 'on-the-fly' mapping.

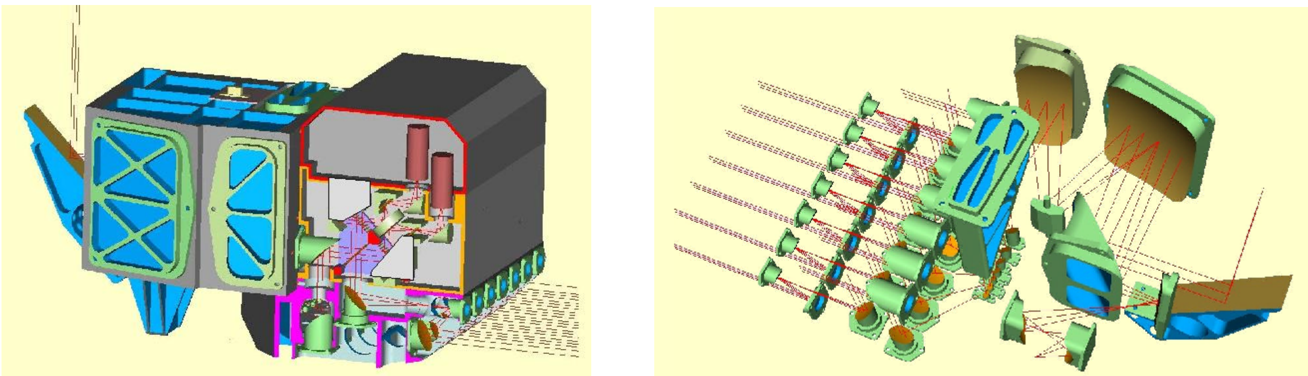

Figure 9. The HIFI focal plane unit. In the left picture the M3 mirror is picking up the signal from the telescope and feeding it into the common optics unit, then into the right the mixer unit, containing the seven mixer subunits, including and the optics combining the signal from the telescope with the local oscillator signal entering from the right. In the right picture an exploded view of the optics.

4. SPACECRAFT AND ORBIT

Budgetary pressures within ESA's scientific programme have forced a reconsideration of the original implementation plans. For FIRST this has meant that synergies have been sought by performing a common implementation with the Planck cosmic microwave background all-sky mapping mission. To this effect several studies were carried out in 1997−98. The option selected is to launch FIRST and Planck together in the so-called 'carrier' configuration, see Figure 10.

Studies subsequent to the 1993 selection (which was based on a concept emplyoing mechanical cryocoolers for payload cooling) have shown that the now well proven ISO cryostat technology could be used to advantage also for FIRST. The FIRST configuration shown in Figures 1 and 10 (see also[7,8]) envisages a payload module based on ISO cryostat technology.

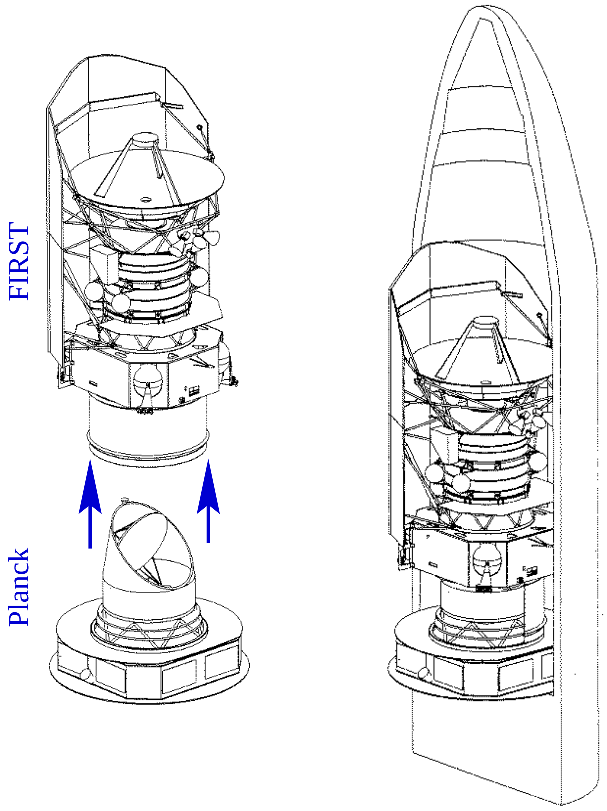

Figure 10. Two views of FIRST and Planck in the 'carrier' configuration. Right: The two satellites in launch configuration, with the FIRST satellite on top of Planck inside the Ariane 5 fairing. Left: The two satellites after separation.

Although detailed design still has to be performed (see Section 7) this configuration has been used to establish payload interfaces and study mission design. It is modular, consisting of a payload module (PLM[9,10]), comprising the superfluid helium cryostat – housing the optical bench with the instrument FPUs – which supports the telescope, star trackers, and some payload associated equipment; and the service module (SVM), which provides the 'infrastructure' and houses the 'warm' payload electronics.

This FIRST concept measures approximately 9 m in height, 4.5 m in width, and has an approximate launch mass of 3200 kg. The 3.5 m diameter FIRST telescope is protected by the sunshade, and will cool passively to around 80 K. The FIRST science payload focal plane units are housed inside the cryostat, which contains superfluid helium at 1.65 K. Fixed solar panels on the sunshade deliver 1 kW power. 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. The mating adaptor remains attached to FIRST after separation.

The Ariane 5 launcher shared by Planck and FIRST will inject both satellites into a transfer trajectory towards the second Lagrangian point (L2) in the Sun-Earth system. They will then separate from the launcher, and subsequently operate independently from orbits of different amplitude around L2.

The L2 point is situated 1.5 million km away from the Earth in the anti-sunward direction. It offers a stable thermal environment with good sky visibility. Since FIRST will be in a large orbit around L2, which has the advantage of not costing any 'orbit injection' Δv, its distance to the Earth will vary between 1.2 and 1.8 million km. The transfer to the operational orbit will last approximately 4 months, after cooldown and outgassing have taken place, it is planned to use this time for commissioning and performance verifications. Once these crucial mission phases have been successfully accomplished, FIRST will go into the routine science operations phase for a minimum duration of 3 years.

5. OBSERVING TIME

The FIRST observation time will be shared between guaranteed and open time. The guaranteed time (approximately one third of the total time) is owned by contributors to the FIRST mission (mainly by the PI instrument consortia) and will be defined by them. The open time will be allocated to the general community (including the guaranteed time holders) on the basis of calls for observing time. A small amount of the open time will be reserved (discretionary time) for targets that could not have been foreseen at the time of a proposal deadline.

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 significant time will be spent on several key programmes.

The planning foresees issuing the call for 'key' programmes approximately three years before the launch, i.e. in early 2004. It will be the first call, and the only call of its kind. It will be followed a year later by the call for the guaranteed time programmes. When the 'key' and guaranteed time programmes have been established, the first of a number of open time calls will be issued; the first one is presently planned to be issued about a year before the launch. It will be followed by additional call(s) at yet to be defined time(s).

6. SCIENCE OPERATIONS

FIRST will be a multi-user observatory open to the general astronomical community. The scientific operations concept is being designed to this effect, including providing an interface to the community at large to keep abreast with FIRST developments as they take place – especially with respect to its predicted scientific capabilities and procedures for applying for observing time – and to provide user support.

The scientific operations of FIRST will be conducted in a novel 'decentralised' manner. The proposed ground segment concept (see also[11]) 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.

In addition it is foreseen that the NASA Infrared Processing and Analysis Center (IPAC) will become a sixth element. 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. The FSC provide all information related to the calls for observing time, and the proposing procedure, as well as general and specific information about 'using' FIRST and its instruments. Proposals are to be submitted to the FSC using the tools provided, and the 'fate' of the proposal can then be tracked by the proposer. For a successful proposal this means being able to see when the proposal becomes scheduled, when it actually has been executed, and whether the observation was successful or not; if not, whether it has been marked for rescheduling.

For a successful observation the data will be available for access by the data owner. At this point the data owner will have the opportunity to request certain data processing to be performed, and to download the data. 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. After the proprietary time has expired for a given data set, these data will be available to the entire community in the same manner they were previously available only to the original owner.

7. STATUS AND SCHEDULE

FIRST is presently in a pre-phase B development phase. The instrument consortia are in the process of finalising the instrument designs in order to start building the first test models. The first formal review cycle, the instrument science verification review (ISVR), has already been conducted, and the resulting actions are being addressed.

Industrial studies are being carried out to further define payload and telescope interfaces, and to refine the cryostat design. These studies are being carried out by industry under contract to ESA. DASA/Dornier has updated instrument interfaces for the FIRST PLM design based on the ISO cryostat technology,[10] while Air Liquide is studying possible alternative cryostat designs, and Alcatel is studying systems optimisation.

JPL and its subcontractors are refining and implementing a telescope development plan. A 2 m diameter 'demonstrator' reflector has been built by Composite Optics Inc., and cold tested. There is also a separate limited effort ongoing related to continuing the backup silicon carbide (SiC) telescope technology development funded by ESA.

The current planning[8] envisages issuing the Invitation to Tender (ITT) for phases B/C/D/E to industry in September 2000, and to start phase B – the detailed design phase – in summer 2001. A series of milestones, including instrument and telescope flight model deliveries in 2004, will lead to a launch early in the year 2007.

Additional information – including online versions of many of the references listed below – can be found on the ESA Astrophysics FIRST World Wide Web site at the following URL: `http://astro.estec.esa.nl/FIRST`.

ACKNOWLEDGMENTS

This paper has been written on behalf of the large number of people who either currently are working on one or more of the many aspects of the FIRST mission – in ESA, the scientific community, and industry – or who have been doing so in the past.

REFERENCES

1. Rowan-Robinson M., Pilbratt G., Wilson A., (eds) 'The Far Infrared and Submillimetre Universe,' ESA **SP−401**, 1997
2. Pilbratt G.L., 'The FIRST ESA Cornerstone Mission,' *Proc. of SPIE* **3356**, pp. 452−461, 1998
3. Connell S.J., Escobedo-Torres J., Friedman Z., Tam A., 'Development progression of an all-composite primary mirror for the FIRST mission,' *Proc. of SPIE* **4013**, this volume, 2000
4. Poglitsch A., Geis N., Waelkens C., 'Photoconductor array camera and spectrometer (PACS) for FIRST,' *Proc. of SPIE* **4013**, this volume, 2000
5. Griffin M., Swinyard B.M., Vigroux L.G., 'SPIRE instrument for FIRST,' *Proc. of SPIE* **4013**, this volume, 2000
6. De Graauw Th., Whyborn N., van de Stadt H. et al, 'Heterodyne instrument for FIRST (HIFI): design and development status,' *Proc. of SPIE* **4013**, this volume, 2000
7. Collaudin B., Paßvogel Th., 'The FIRST and Planck 'carrier' missions: Description of the cryogenic systems' *Proc. of 1998 Space Cryogenics Workshop,* ESA **WPP−157**, 111−122, 1998
8. Passvogel Th., Felici F., 'The FIRST/Planck Programme: Current Status,' *Proc. of SPIE* **4013**, this volume, 2000
9. Schupp J., Moßbacher B., Seidel A., 'The FIRST PLM based on a HeII cryostat' *Proc. of 1998 Space Cryogenics Workshop,* ESA **WPP−157**, 107−110, 1998
10. Collaudin B., Schupp J., Hauser A., Wagner A., 'FIRST Payload Module and Accomodation of Instruments,' *Proc. of SPIE* **4013**, this volume, 2000
11. Bauer O.H., Estaria P., King K.J., Pilbratt G., Robson A., Roelfsema, P.R., Schaap H., 'FIRST Ground Segment and Science Operations Concept' *Proc. of SPIE* **3349**, 312−318, 1998