The Extragalactic Infrared Background and its Cosmological Implications
IAU Symposium, Vol. 204, 2001
Martin Harwit and Michael G. Hauser, eds.

The FIRST ESA Cornerstone Mission

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

The key science objectives emphasize current questions connected to the formation of galaxies and stars, however, having unique capabilities in several ways.

FIRST, a facility available to the entire astronomical community, will carry a 3.5 metre diameter passively cooled telescope. The science payload complement – two cameras/medium resolution spectrometers (PACS and SPIRE), and a very high resolution heterodyne spectrometer (HIFI) – will be housed in a superfluid helium cryostat.

In early 2007, FIRST will be placed in a transfer trajectory towards its operational orbit around the Earth-Sun L2 point by an Ariane 5 (shared with the ESA cosmic background mapping mission, Planck). 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.

1. Introduction

The 'Far InfraRed and Submillimetre Telescope' (FIRST, cf. Fig. 1) 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 observing opportunities for the entire astronomical community. FIRST is the fourth of the 'cornerstone' missions in the ESA science 'Horizon 2000' plan.

FIRST is the only space facility dedicated to the submillimetre and far infrared part of the spectrum. Its vantage point in space provides several decisive advantages. The telescope will be passively cooled, which together with a low emissivity and the total absence of (even residual) atmospheric emission offers a very low and stable background that enables sensitive photometric observations. Furthermore, the absence of atmospheric absorption gives full access to the entire

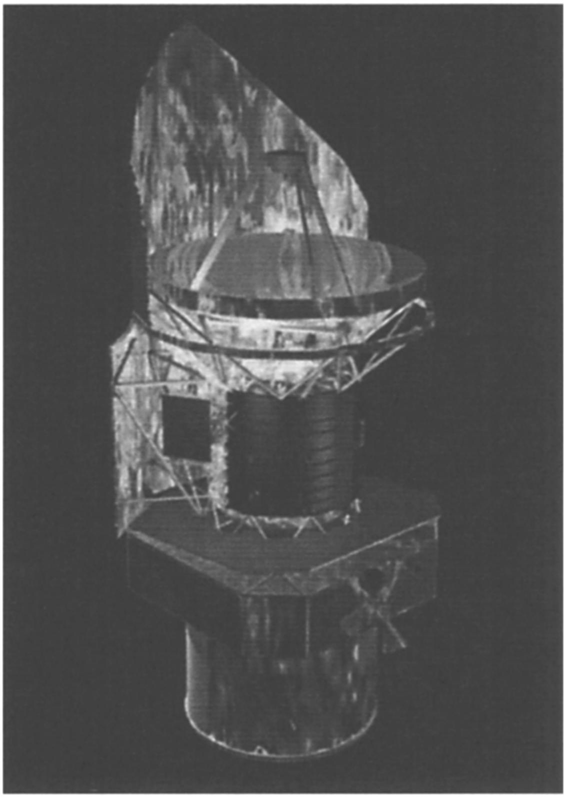

Figure 1. The FIRST satellite in orbit. The passively cooled telescope behind its protective sunshade, the superfluid helium cryostat containing the science instruments, and the service module are all clearly visible. (Courtesy Alcatel Space Systems.)

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 (cf. Rowan-Robinson et al. 1997; Pilbratt 2000) 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 parts of 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:

- Deep extragalactic 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 few Gyr in the development 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 provide 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 and 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.

- 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.

All astronomy missions and observatories – ground, air, and space based – to varying degrees rely on and complement each other. A major strength of FIRST is its photometric mapping capability for performing unbiased surveys related to galaxy and star formation. Redshifted ultraluminous IRAS galaxies (with SEDs that 'peak' in the 50–100 μm range in their rest frames) as well as class 0 protostars and prestellar objects peak in the FIRST 'prime' band; cf. Fig. 2. FIRST is also well equipped to perform spectroscopic follow-up observations to further characterise particularly interesting individual objects.

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 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!

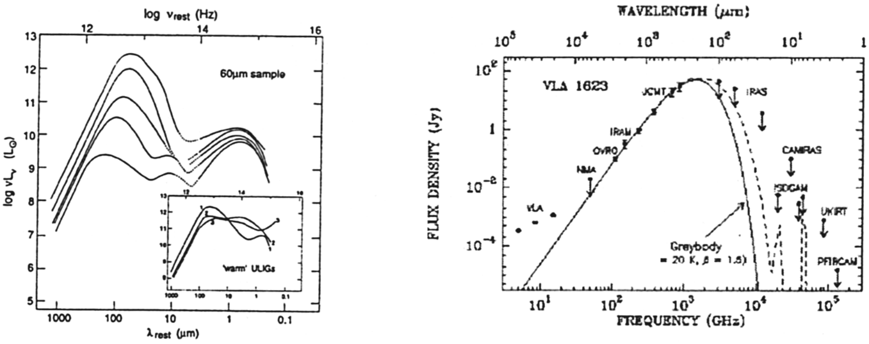

Figure 2. The FIRST wavelength coverage is ideally suited to observing redshifted luminous IRAS galaxies (left) and class 0 protostars (right). Observations with PACS and SPIRE will enable large-scale unbiased searches for such sources, and determine their bolometric luminosities.

3. Telescope and Science Payload

In order to fully exploit the favourable conditions offered 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; the instruments will be housed inside a superfluid helium cryostat.

3.1. Telescope Development

The FIRST telescope must have very low emissivity and 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 of 90 μm). Being protected by a fixed sunshade, it will radiatively cool to an operational temperature of around 80 K in orbit. The present planning assumes that this telescope will be provided by NASA.

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 precisely machined to correct for low spatial frequency imperfections in the primary. An aggressive development programme is underway (cf. Connell et al. 2000) 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 complement 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 by the ESA Science Programme Committee in May 1998 and approved in February 1999, based on the response to an Announcement of Opportunity (AO) issued in October 1997.

It consists of the following three instruments which will be provided by consortia led by Principal Investigators (PIs):

- 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.

3.2.1. PACS - a Camera and Spectrometer

PACS (cf. Poglitsch et al. 2000) is a camera and low to medium resolution spectrometer for wavelengths up to ~ 210 μm. It has recently been redesigned to employ in total four detector arrays, two 'new' bolometer arrays in addition to the two 'existing' photoconductor arrays. The bolometer arrays are dedicated for photometry, and the Ge:Ga detector arrays are to be employed exclusively for spectroscopy (cf. Figs. 3 & 4). PACS can be operated either as an imaging photometer, or as an integral field line spectrometer.

PACS has three photometric bands with $R \sim 2$. The short wavelength 'blue' array covers the 60–90 and 90–130 μm bands, while the 'red' array covers the 130–210 μm band. In photometric mode, one of the 'blue' bands and the 'red' band are observed simultaneously. The two bolometer arrays both fully sample the same $1\farcm75 \times 3\farcm5$ field of view on the sky, and provide a predicted point source detection limit of ~ 3 mJy (5σ, 1 hour) in all three bands. An internal ^{3}He sorption cooler will provide the 300 mK environment needed by the bolometers.

For spectroscopy, PACS covers 57–210 μm in three contiguous bands, providing a velocity resolution in the range 150–200 km sec^{-1} and an instantaneous coverage of ~ 1500 km sec^{-1}. The two Ge:Ga 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 predicted point source detection limit is $\sim 3 \times 10^{-18}$ Wm^{-2} (5σ, 1 hour) over most of the band, rising to $\sim 8 \times 10^{-18}$ Wm^{-2} for the shortest wavelengths.

3.2.2. SPIRE - a Camera and Spectrometer

SPIRE (cf. Griffin et al. 2000) is a camera and low to medium resolution spectrometer for wavelengths above ~ 200 μm. It comprises an imaging photometer

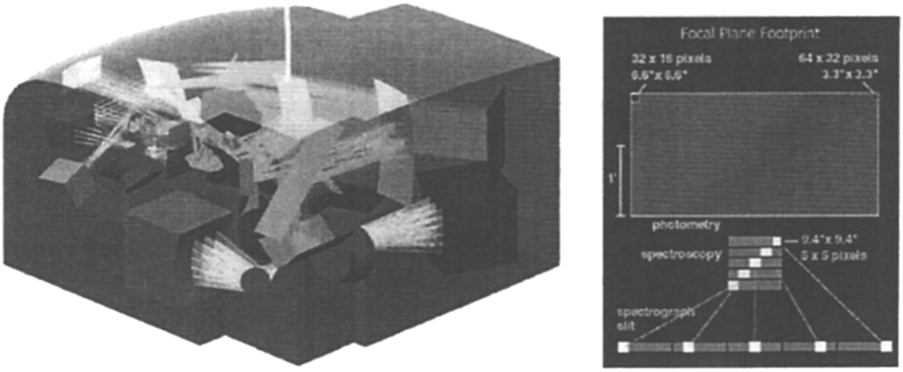

Figure 3. Left: A computer rendering of the PACS focal plane unit optics. The bolometer arrays are visible towards the extreme left, the photoconductor arrays are the two large 'cubes' respectively. Right: The PACS focal plane footprint.

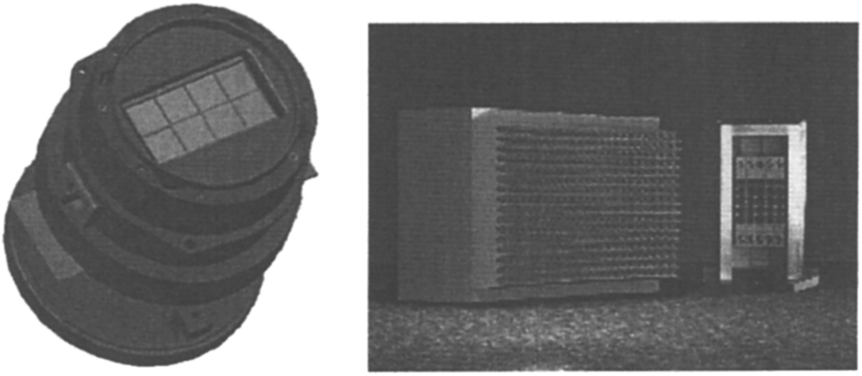

Figure 4. Left: The PACS 'blue' bolometer array. The 8 16×16 bolometer subarrays are visible. Right: A computer rendering of a PACS stressed Ge:Ga array consisting of 25 individual linear arrays with 16 pixels each, compared to the 5×5 FIFI array used on KAO.

and a Fourier Transform Spectrometer (FTS), both of which use bolometer detector arrays. There are a total of five arrays, three dedicated for photometry and two for spectroscopy (cf. Figs. 5 & 6). All employ 'spider-web' bolometers with NTD Ge temperature sensors, each pixel being fed by a single-mode $2F\lambda$

feedhorn, and JFET readout electronics. The bolometers are cooled to 300 mK by an internal ^{3}He sorption cooler.

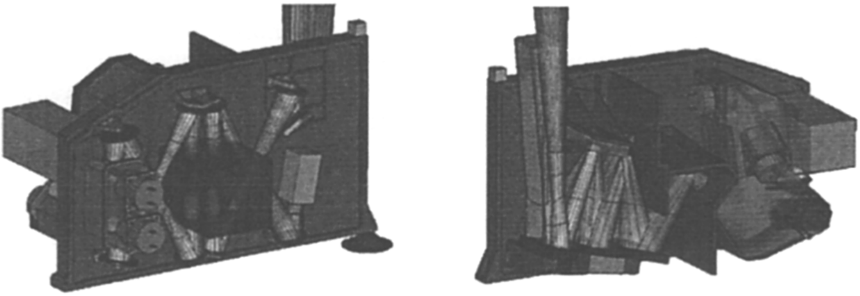

Figure 5. Right: The SPIRE photometer; its three bolometer arrays are towards the right. Left: The spectrometer, in the middle of the mirror mechanism box, and on the left its two bolometer arrays. All five detector arrays are situated close to the internal ^{3}He sorption cooler which provides the 300 mK operating temperature.

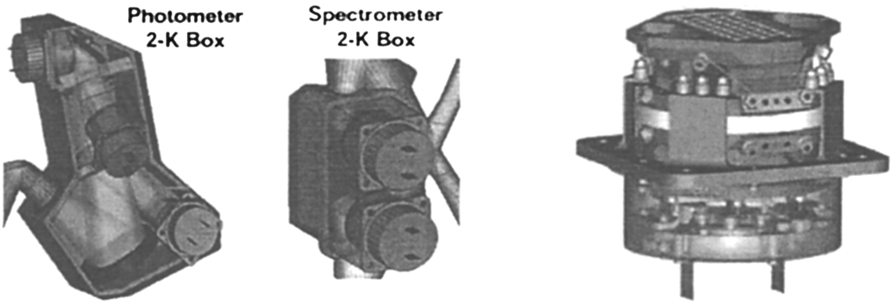

Figure 6. Left: Close-up of the two 2 K enclosures housing the bolometer arrays. Right: One of the bolometer arrays.

SPIRE has been designed to maximise mapping speed. In its broadband ($R \sim 3$) photometry mode it simultaneously images a $4' \times 8'$ field on the sky in three colours centred on 250, 350, and 500 μm. 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. The SPIRE point source sensitivity is predicted to be in the range 5–7 mJy (5σ, 1 hour). Since the confusion limit for extragalactic surveys is estimated to lie in the range 10–20 mJy, SPIRE will be able to map roughly 1 square degree on the sky per day to its confusion limit.

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 $\sim 2.6'$.

3.2.3. HIFI - a Very High Resolution Heterodyne Spectrometer

HIFI is a very high resolution heterodyne spectrometer. It offers velocity resolution in the range 0.3–300 km sec^{-1}, combined with low noise detection using superconductor-insulator-superconductor (SIS) and hot electron bolometer (HEB) mixers. HIFI is not an imaging instrument: it probes a single pixel on the sky.

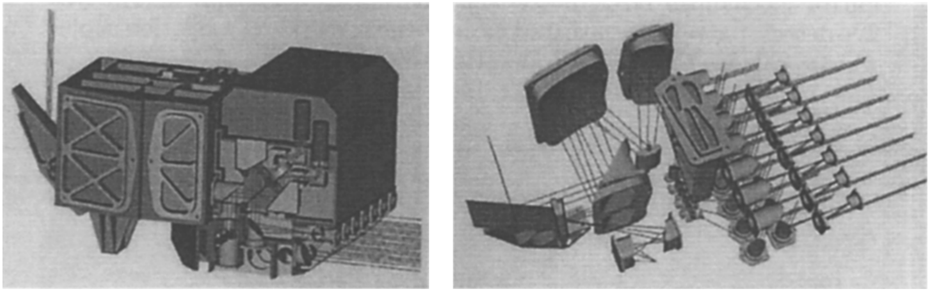

Figure 7. The HIFI focal plane unit. Left: The signal from the telescope is fed into the common optics unit by the M3 mirror. It is then combined with the local oscillator signal and fed to the mixers. Right: An exploded view of the optics.

The focal plane unit (FPU, cf. Fig. 7), houses seven mixer assemblies, each 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 GHz band. The FPU also houses the optics that feed the mixers the signal from the telescope, and combines it with the appropriate local oscillator (LO) signal. It also 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, cf. 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 complement of backend spectrometers.

4. Spacecraft and Orbit

The FIRST configuration shown in Fig. 1 (cf. Passvogel & Felici 2000) envisages a payload module based on the now well proven ISO cryostat technology. This configuration has been used to establish payload interfaces and study mission design. It is modular, consisting of a payload module (PLM, cf. Collaudin et al. 2000), and a service module (SVM). The payload comprises the superfluid helium cryostat – housing the optical bench with the instrument FPUs, cf. Fig. 8 – which supports the telescope, star trackers, and some payload associated equipment. The service module (SVM), which provides the 'infrastructure' and houses the 'warm' payload electronics.

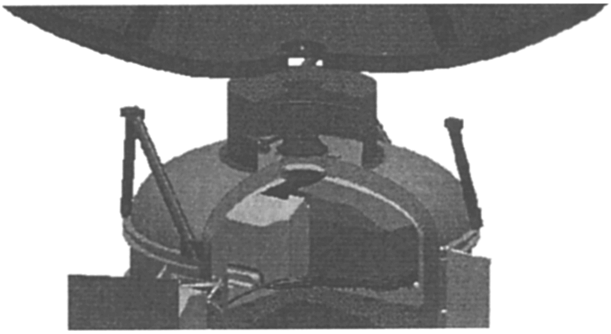

Figure 8. Exploded view of the upper part of the FIRST payload module, showing the three instrument focal plane units on the optical bench on top of the superfluid helium tank inside the cryostat vacuum vessel. (Courtesy Astrium.)

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.

An Ariane 5 launcher (Fig. 9), shared by FIRST and the ESA CMB mapping mission, Planck, 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-Sun direction (cf. Fig. 9). It offers a stable thermal environment with good

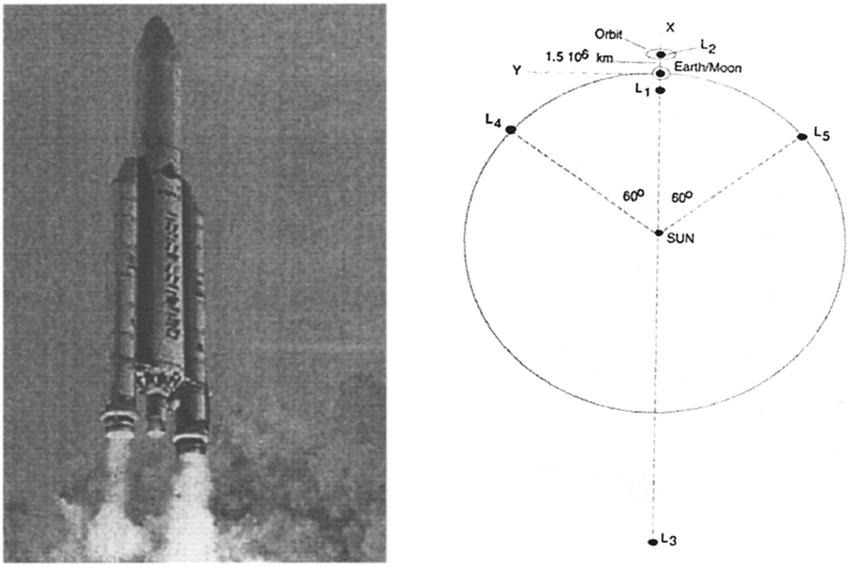

Figure 9. Left: A single Ariane 5 launcher will place both FIRST and Planck in transfer trajectories towards L2. Right: L2 is situated 0.01 AU from the Earth in the anti-Sun direction, providing a thermally stable, favourable vantage point for carrying out observations.

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. Science Operations

FIRST will be a multi-user observatory open to the general astronomical community. The observing 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), whereas 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 (discretionary time) will be reserved for targets that could not have been foreseen at the time of a proposal deadline.

The scientific operations of FIRST will be conducted in a novel 'decentralised' manner. The proposed ground segment concept (cf. also Bauer et al. 1998) 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 FIRST Science Center at the Infrared Processing and Analysis Center (IPAC) will become the sixth element.

The FSC acts as the single-point interface to the science community and outside world in general. The FSC provides information and user support related to the entire life-cycle of an observation, from calls for observing time, the proposing procedure, proposal tracking, data access and data processing, as well as general and specific information about 'using' FIRST and its instruments.

All scientific data will be archived and made available to the data owners. 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.

6. Status and Schedule

FIRST is presently in a pre-phase B development phase. Industrial studies have been carried out to define payload and telescope interfaces, and to refine the cryostat design. 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 been successfully conducted.

The Invitation to Tender (ITT) to industry for phases B/C/D/E was issued on schedule on 1 September 2000 with a deadline for proposals of 1 December 2000. The detailed design phase – phase B – will start on 1 June 2001, after a prime contractor has been selected. The current planning (cf. Passvogel & Felici 2000) envisages a series of milestones, including instrument and telescope flight model deliveries in 2004, to be followed by spacecraft integration and extensive system level ground testing, leading to a launch nominally on 15 February 2007.

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

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