FIRST – FAR INFRARED AND SUBMILLIMETRE SPACE TELESCOPE

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Abstract. FIRST is an element of the ESA long term science program. Currently in a detailed study phase it is foreseen as a large (4.5–8 m) diameter passively cooled telescope equipped with a combination of photometer/camera and very high resolution spectrometers. The spectrometers will utilize both direct detection and heterodyne techniques to cover the wavelength band 85–600 micron. The photometers will have both bolometer and photoconductor detector arrays. FIRST is foreseen to be launched shortly after the year 2000 and will be operated as a facility open to the wide scientific community.

1. Introduction

The European Space Agency ESA is studying a large Far-Infrared and Submillimetre Space Telescope (FIRST). The submillimetre range is severely blocked by atmospheric absorption as is clearly demonstrated in Figure 1.

FIRST will open up this virtually unexplored waveband of the electromagnetic spectrum between just below 100 micron and 1 mm for detailed astrophysical measurements.

The planned 4 to 8 m diameter telescope will for the first time allow arcsecond imaging in this wavelength region and, with its high throughput and low thermal background, will result in superb sensitivity for both photometry and spectroscopy. Multi-band high-resolution spectrometers will give unprecedented information on the physics, chemistry and dynamics of interstellar, circumstellar, planetary and

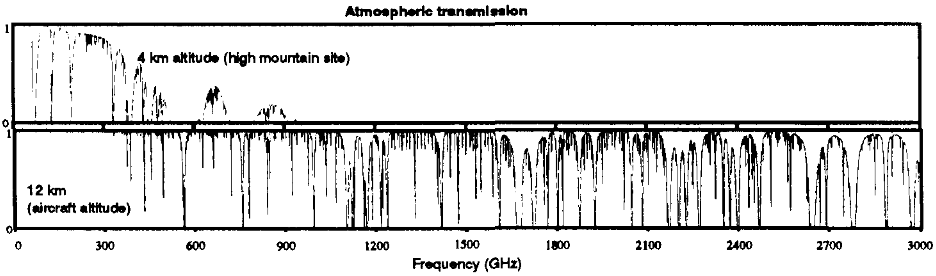

Fig. 1. Transmission of the atmosphere from a 4 km altitude mountain and from the altitude of an airborne telescope such as the Kuiper Airborne Observatory. The blocked regions are caused mostly by molecular line absorption. Many of these lines are the same as of astrophysical interest and cannot even be observed from aircraft altitude.

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cometary gas and dust. The ESA Cornerstone FIRST will be a multi-purpose observatory serving the entire astronomical community. It will explore and contribute to a wide range of important problems in modern astronomy and astrophysics.

The concept of FIRST calls for a free-flyer, with a passively cooled telescope which is protected by a thermal shield. The focal plane instruments will be cryogenically cooled by superfluid Helium, and/or by mechanical coolers.

The telescope will have a surface accuracy of about 8 mm r.m.s. in order to efficiently operate at wavelengths as short as about 100 micron, with a possible extension to 50 micron. At a wavelength of 100 micron, the resolution will be 3.5 arc sec for the 8 metre version. As such FIRST will have an angular resolution more than an order of magnitude better than the NASA Kuiper Airborne Observatory (KAO), the Infrared Astronomical Satellite (IRAS), or the ESA Infrared Space Observatory (ISO) at the same wavelengths; objects which IRAS was able to resolve in our Galaxy can be resolved by FIRST in nearby galaxies of the Local Group. FIRST will have an angular resolution comparable to, or approaching that of current ground-based telescopes and will thus allow a direct comparison of molecular material mapped at millimetre or infrared wavelengths from the ground and at far-infrared wavelengths from space. By virtue of its large size, low temperature and emissivity, and location in space FIRST will be 100 to 1000 times more sensitive than the KAO, and at least ten times more sensitive than the Long Wavelength Spectrometer (LWS) on ISO or the largest ground-based submillimetre telescope. FIRST will be able to do detailed 100 micron to 1 mm spectroscopy of the cold and warm components of the Universe out to cosmological distances.

2. Scientific impact of FIRST

FIRST will open up the last major part of of the electromagnetic spectrum still mostly out of reach of astronomers. Each time a new window in the spectrum is opened and an observatory facility is made available, a large variety of scientific objectives appears, and results benefit almost every subject in astrophysics. Furthermore, new and unpredictable scientific problems arise often with the most original outcome. Undoubtedly the same will be true in the submillimetre part of the spectrum. However, with the knowledge we have today we expect the major impact of FIRST to occur in the following areas:

- Physics of the interstellar medium including its chemistry and dynamics both in our and external galaxies.
- Physics of star formation galaxies and in particular its variation from galaxy to galaxy.
- Studies of early evolution of galaxies.
- Properties of primitive solar system material.

As an example, Figure 2 gives an overview of the rich abundance of spectral lines of molecular atoms and ions in the far-infrared and submillimetre waveband.

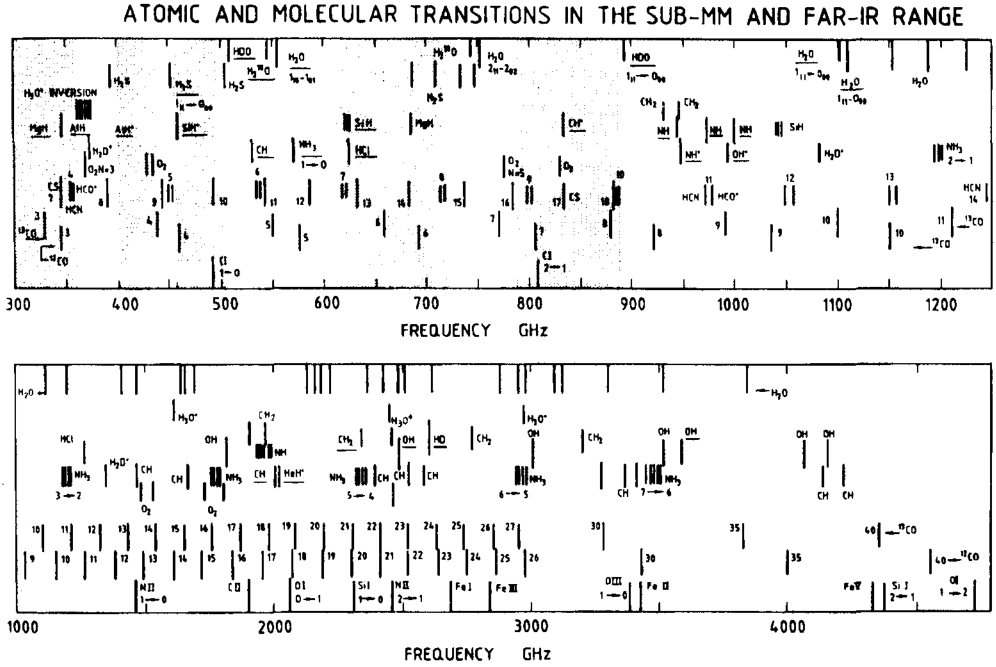

Fig. 2. Some of the important atomic and molecular transitions covered by FIRST. The upper inset gives the frequency range covered by the heterodyne spectrometers, the lower the range (1000 to > 3000 GHz) likely covered by the imaging direct detection spectrometer. Rotational transitions are marked by their upper J–value (e.g. ^{12}CO 10 for $J = 10 \rightarrow 9$). Underlining denotes transitions connecting to the ground state of the species. Shaded zones mark frequency ranges that can be observed from the ground.

3. Spacecraft, telescope and orbit

The currently foreseen spacecraft for FIRST is three-axis stabilized by means of momentum wheels. The attitude information is provided by star trackers mounted in close connection to the telescope structure. The calibration of these sensors with respect to the payload viewing direction is performed in orbit by determining the offset of the star trackers from the focal plane sensors at far-infrared wavelengths.

Power comes from fixed body-mounted solar arrays. This limits the instantaneously available fraction of the sky for observation at any given time of the year to less than 50%. Orbital motion of the Earth around the Sun enables different portions of the sky to be viewed at different times during the year very much like from the ground. Like other spacecraft FIRST will have on-board batteries to provide power in periods of eclipse. During all but the very short eclipses scientific operations would be suspended to save power. Over the 6 year lifetime only one period of very long (3.5 hours) eclipses occurs. If cryo-coolers are used then cooling will be suspended during this period and the payload would be allowed to warm up to about 100 K. The choice of a limited range of solar aspect angles also help

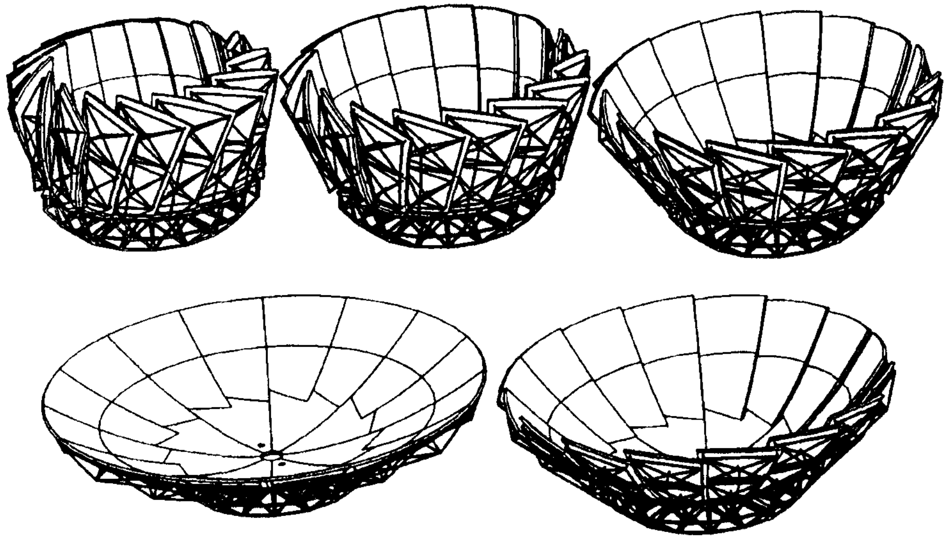

Fig. 3. A sequence of drawings showing how the 8 metre diameter reflector deploys from its stowed to operational state. Each deployable petal is rotating around a single inclined hinge and driven by the same drive system. Synchronism is maintained by the design and requires no additional mechanisms.

to simplify the thermal design. This is important both when coolers and when a cryostat is used.

The telescope for FIRST will be similar in concept to modern ground-based submillimetre antennas. The surface will be made up of panels or sections. Depending on the size of the antenna these sections may be launched in a folded up configuration and then deployed in orbit. The goal for the FIRST antenna is for an overall accuracy of 8 mm rms including allowances for the secondary mirror.

The most promising material for the telescope panels is Carbon-Fibre Reinforced Plastic (CFRP). It is light, strong and thermally stable. CFRP can be "layed-up" over precision moulds to form the exact curved shape required for the reflector and then the epoxy can be "cured" by heating. A spacer that could also be made of CFRP can then be bonded onto the back of the reflector and a further skin added to form a sandwich panel which has very high stiffness but low weight. This technique has been developed for a number of large ground-based telescopes working at millimetre wavelengths and on numerous smaller antennae on spacecraft. Accuracy of better than 2 micron rms has been demonstrated on panels nearly 2 metres in size.

The CFRP panels will be supported by a stiff framework. This frame would also be made primarily from CFRP, this time in the form of tubes. If the diameter is to be as large as 8 metres, the antenna will have to be folded for launch and then unfurled, once in orbit, rather like an opening flower shown in Figure 3.

In this case the structure will incorporate a hinge mechanism to allow for folding. Such a mechanism is currently under development and testing.

The other main component of the antenna is the secondary mirror. It is likely that it will be necessary to provide mechanisms for moving this mirror to the correct position to give the best focussing of the image. A possible further refinement is to make the secondary mirror "wobble" from side to side during observations, this is normally referred to as chopping. The effect of this is to move the image of the astronomical source on and off the detector so that its signals can be separated from the emission from the antenna.

Finally the thermal shield around the whole assembly plays a vital role in protecting the antenna from the solar radiation which would otherwise cause steep temperature gradients across the exposed structures, inevitably introducing severe deformations into the structure despite the use of low-expansion materials. This shield will be constructed of multiple layers of very thin plastic, coated with highly reflecting aluminium and supported by a structure. The shield needs to be large – roughly 10 by 5 metres – and therefore must again be erected in orbit. However very little weight can be assigned to this item. Methods of making such structures have recently been developed. These use inflatable tubes impregnated with a resin that hardens when exposed to the heat from the sun. The thermal shield can therefore be folded for launch, then inflated by a gas when the spacecraft reaches its orbit. The material will harden after a few hours so that the shield will keep its shape indefinitely after the gas is vented. Encased in this protective shield the antenna will cool to about 150 K. This will reduce the background signal emitted from its surface, and differences between the temperatures of its vital parts will be no greater than a few degrees, ensuring that the high accuracy of the antenna will be main tained. The structure for such a thermal shield has been showed in Figure 4 during testing at Contraves.

The whole package will be put in orbit by an Ariane 5 launcher. A highly elliptical 24 hour orbit (apogee altitude 70600 km. perigee altitude 1000 km) appears to best satisfy the combined requirements of low launch cost, large uninterrupted periods and an environment which is both thermally very stable and has a low density of energetic particles.

4. Cooling

There are three classes of thermal control on FIRST: that of the telescope, classical thermal control of space craft systems and the cooling of the payload. The telescope is cooled passively, heat leaking through the thermal shield is radiated into cold space. The equilibrium temperature is around 150 K. It is important that this temperature is stable since large fluctuations would degrade telescope and payload performance. This is achieved by proper design of the thermal shield. However, during the short but close to Earth perigee it is not possible to completely avoid upsetting the thermal equilibrium of the antenna. Therefore (and also because the spacecraft is passing through the radiation belts) observations are suspended during this period. The payload makes use of two different technologies, heterodyne detection and direct detection. In case of the first only the downconverters need low temperatures. The superconducting tunneling junctions used as mixers in the heterodyne receivers about 4–5 K and the associated cold amplifiers about 20–

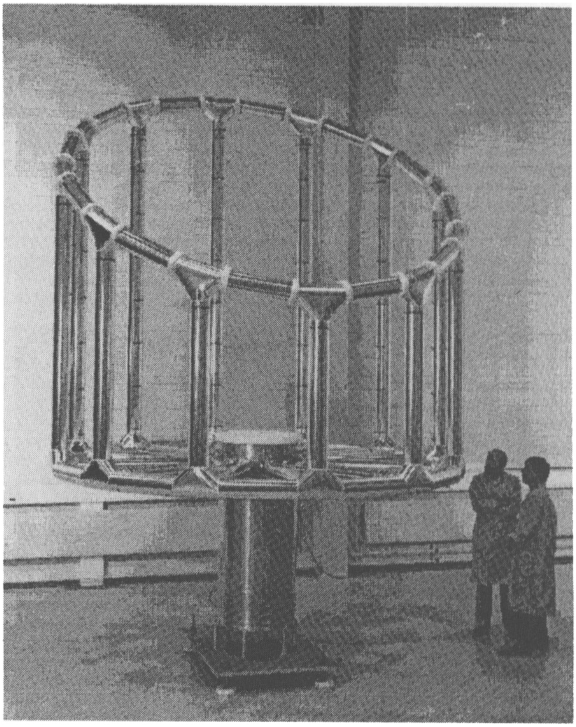

Fig. 4. The FIRST heat shield as a 1/3 scale model during testing at CONTRAVES. The tubes support Multi-Layer Insulation (MLI) used to reject heat from the Sun and from Earth in order to maintain a stable thermal environment for the FIRST antenna.

30 K. The cold volume is small and we thus refer to this as point cooling. The direct detection instruments use optical methods to achieve their spectral resolution. Since the detectors are performance limited by the thermal background it is important that the thermal radiation from these optical elements is low compared to that from the telescope when spectrally filtered. Hence, large parts of these instruments have to be kept cold (about 7 K). This constitutes a need for volume cooling. The detectors require about 2–4 K operating temperature but have a relatively small volume. Two methods can be used to lift heat at these temperatures: long-life mechanical coolers and the heat capacity of stored cryogens such as superfluid helium. Mechanical cooler developments are on-going within the ESA technology program, see Figure 5.

These are expected to have reached a mature state before the hardware development of FIRST begins. Storing cryogen and using it to cool infrared detectors is a flight proven technique and will also be used for the ISO. Coolers are well suited for point cooling and stored cryogen for volume cooling. The choice for FIRST could be either one or a combination of both.

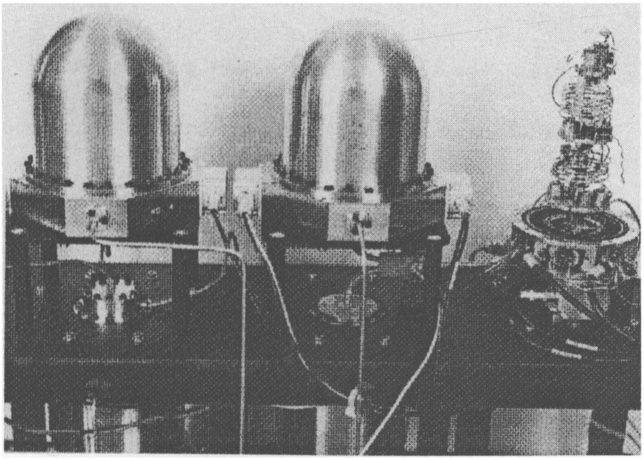

Fig. 5. This figure shows the demonstration model of the 4 K cooler with one pair of compressors for the stirling cycle and one for the JT stage. The two stage displacer for the stirling cycle with heat exchangers and JT valve on the top is seen to the right.

5. The payload

FIRST will have a full complement of instruments for high and medium resolution spectroscopy, imaging and photometry over the entire range of 80 micron to about 1 mm.

The current plan calls for:
– several sensitive heterodyne receivers covering a significant fraction of the 500 to 1200 GHz range. The heterodyne receivers will provide 0.3 km/s spectral resolution with 2 GHz instantaneous bandwidth. The mixers will be SIS junctions pumped by solid state local oscillators.
– a far-infrared imaging spectrometer covering the 80 to 200 micron range with a Ge:Ga detector array (7 × 7 pixels). Spectral resolution will be selectable in the range of 0.3 km/s to 1000 km/s. Incorporation of a bolometer array may extend the wavelength coverage to longward of 200 micon.
– an imaging photometer for the range 50 to 850 micron, with a 20 × 20 array of Ge:Ga photoconductors for the far-IR near 100 micron and a 2 × 2 array of bolometers for observations near 700 micron.

6. Status of FIRST

Currently a system level study is being carried out by an industrial consortium led by Dornier. The aim of this study is to improve our understanding and definition of the project and to identify areas of technology that need further development. The Science Advisory Group (SAG) consisting of scientists from ESA member countries helps ESA in making decisions where scientific trade-offs are involved. Two further groups: the Payload Working Group (PWG) and the Telescope Working Group (TWG) provide detailed definitions of the model payload and the telescope requirements. This phase was started in 1989 and will end in 1991. During this period major decisions on the design will be made.

Following the completion of this study phase, technology development will be initiated as required lasting up to 1995–96. Assuming that a decision is taken to implement this project as the third cornerstone the project will enter into a detailed design phase followed by hardware development in 1996. The payload that will be built by national institutes will have been selected before this date. The currently foreseen launch with an Ariane vehicle would occur during 2002–3.