The SPIRE instrument for FIRST

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ABSTRACT

SPIRE, the Spectral and Photometric Imaging Receiver, will be a bolometer instrument for ESA's FIRST satellite. Its main scientific goals are deep extragalactic and galactic imaging surveys and spectroscopy of star-forming regions in own and nearby galaxies. The SPIRE detectors are feedhorn-coupled NTD spider-web bolometers. The instrument comprises a three-band imaging photometer covering the 250-500 μm range, and an imaging Fourier Transform Spectrometer (FTS) covering 200-670 μm. The photometer has a field of view of 4 x 8 arcminutes which is observed simultaneously at 250, 350 and 500 μm, with dichroic beam dividers separating the three spectral bands. Its angular resolution is determined by the telescope diffraction limit, with FWHM beam widths of approximately 17, 24 and 35 arcseconds at 250, 350 and 500 μm, respectively. An internal beam steering mirror can be used for spatial modulation of the telescope beam, and observations can also be made by scanning the telescope without chopping, providing better sensitivity for source confusion-limited deep surveys. The FTS has a field of view of 2.6 arcminutes and an adjustable spectral resolution of 0.04 - 2 cm^{-1} ($\lambda/\Delta\lambda$ = 20 - 1000 at 250 μm). It employs a dual-beam configuration with novel broad-band intensity beam dividers to provide high efficiency and separated output and input ports.

Keywords: FIRST, Far Infrared, Submillimetre, Bolometer, Instrumentation

1 INTRODUCTION

SPIRE (the Spectral and Photometric Imaging REceiver) is one of three cryogenic focal plane instruments for ESA's FIRST mission[1]. Its main scientific goals are the investigation of the statistics and physics of galaxy and structure formation at high redshift and the study of the earliest stages of star formation, when the protostar is still coupled to the interstellar medium. These studies require the capabilities to carry out large-area (many tens of square degrees) deep photometric imaging surveys at far-infrared and submillimetre wavelengths, and to follow up these systematic survey observations with spectroscopy of selected sources. SPIRE will exploit the advantages of FIRST: its large-aperture, cold, low-emissivity telescope; the complete lack of atmospheric emission and attenuation giving access to the poorly explored 200-700-μm range, and the large amount of high quality observing time. Because of these advantages, SPIRE will have unmatched sensitivity for deep imaging photometry and moderate-resolution spectroscopy.

Galaxies emit a large amount (from 30% to nearly 100%) of their energy in the far infrared due to re-processing of stellar UV radiation by interstellar dust grains. The far infrared peak is redshifted into the SPIRE wavelength range for galaxies with redshift, z, greater than ~ 1. The total luminosity of a galaxy cannot be determined without an accurate measurement of its Spectral Energy Distribution (SED). The study of the early stages of galaxy evolution thus requires an instrument that can detect emission from high-z galaxies in the submillimetre, enabling their SEDs and luminosities to be derived. The pioneering observations made with the SCUBA submillimetre camera on the JCMT have emphasised the importance of the FIR-submillimetre band for studies of the high-redshift universe[2].

Stars form through the fragmentation and collapse of dense cloud cores in the interstellar medium (ISM), and the very first stages of this process are not well known. A good understanding of this early evolution is crucial, as it governs the origin of the stellar initial mass function (IMF). Sensitive far infrared and submillimetre observations with high spatial resolution are necessary to

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make complete surveys of protostellar clumps to determine their bolometric luminosities and mass functions. SPIRE will also, for the first time, enable astronomers to observe at high spatial resolution the physical and chemical conditions prevailing in the cold phases of the interstellar medium and to study the behavior of the interstellar gas and dust before and during star formation. SPIRE's uniquely high sensitivity to very cold dust emission also makes it the ideal instrument to study the material that is ejected in copious quantities from evolved stars, enriching the interstellar medium with heavy elements. Large amounts of matter - as yet undetected - are ejected from stars before the white dwarf stage. Theories of stellar evolution, and of the enrichment of galaxies in heavy elements and dust, will be incomplete until these earlier mass loss phases are characterised and understood. Studies of star formation and of the interaction of forming and evolved stars with the ISM are also, of course, intimately related to the investigation of galaxy formation and evolution, which occur through just these processes.

These high priority programmes for FIRST require sensitive continuum imaging in several bands to carry out surveys, and a low-resolution spectroscopic mode to obtain detailed SEDs of selected objects and measure key spectral lines. Although SPIRE has been optimised for these two main scientific programmes, it will offer the astronomical community a powerful tool for many other astrophysical studies: giant planets, comets, the galactic interstellar medium, nearby galaxies, ultraluminous infrared galaxies, and active galactic nuclei. Its capabilities will remain unchallenged by the ground-based and the airborne observatories which are planned to come into operation over the next decade.

In this paper we present an update on the SPIRE instrument design, which has been refined and improved since its description[3] at the Kona SPIE meeting in 1998.

2 INSTRUMENT OVERVIEW

SPIRE contains a three-band imaging photometer and an imaging Fourier Transform Spectrometer (FTS), both of which use 0.3-K feedhorn-coupled "spider-web" NTD germanium bolometers cooled by a ^{3}He refrigerator. The photometer and spectrometer are not designed to operate simultaneously. The field of view of the photometer is 4 x 8 arcminute, the largest that can be achieved given the location of the SPIRE field of view in the FIRST focal plane and the size of the telescope unvignetted field of view. Three bolometer arrays provide broad-band photometry ($\lambda/\Delta\lambda \approx 3$) in wavelength bands centred on 250, 350 and 500 μm. The field of view is observed simultaneously in all three bands through the use of fixed dichroic beam-splitters. Spatial modulation can be provided either by a Beam Steering Mirror (BSM) in the instrument or by drift scanning the telescope across the sky, depending on the type of observation. An internal thermal calibration source is available to provide a repeatable calibration signal for the detectors. The FTS uses novel broadband intensity beam dividers, and combines high efficiency with spatially separated input ports. One input port covers a 2.6-arcminute diameter field of view on the sky and the other is fed by an on-board calibration source. Two bolometer arrays are located at the output ports, one covering 200-300 μm and the other 300-670 μm. The FTS will be operated in continuous scan mode, with the path difference between the two arms of the interferometer being changed by a constant-speed mirror drive mechanism. The spectral resolution, as determined by the maximum optical path difference, will be adjustable between 0.04 and 2 cm^{-1} (corresponding to $\lambda/\Delta\lambda$ = 1000 - 20 at 250 μm wavelength).

The focal plane unit is 690 x 410 x 410 mm in size, and has three separate temperature stages at nominal temperatures of 4 K, 2 K (provided by the FIRST cryostat) and 300 mK (provided by SPIRE's internal cooler). The main 4-K structural element of the FPU is an optical bench panel which is supported from the 10-K cryostat optical bench by stainless steel blade mounts. The photometer and spectrometer are located on either side of this panel. The majority of the optics are at 4 K, but the detector arrays and final optics are contained within 2-K enclosures. The ^{3}He refrigerator cools all of the five detector arrays to 0.3 K. A JFET preamplifier module is attached to the 10 K optical bench close to the 4-K enclosure, with the JFETs heated internally to their optimum operating temperature of ~ 120 K.

The detector signals are amplified in a Buffer Amplifier Unit (BAU) located on the outside of the 80-K FIRST cryostat. The SPIRE warm electronics consist of a Detector Readout and Control Unit (DRCU) and a Digital Processing Unit (DPU). The DRCU provides bias and signal conditioning for the arrays and cold readout electronics, reads out the detector signals, and controls the FPU mechanisms and the ^{3}He cooler. The DPU acts as the interface to the spacecraft, including instrument commanding and formats science and housekeeping data for telemetry to the ground.

3 IMAGING PHOTOMETER

3.1 OPTICAL DESIGN AND FPU LAYOUT

The photometer layout is shown in Fig. 1. The 4-K optical elements are mounted directly from the optical bench panel. The 2-K enclosure is also supported from the panel by stainless steel blades, and contains the detector arrays, the dichroics and fold mirrors. The three array modules are bolted to the outside wall of the 2-K box. Within each module, the detector arrays, feedhorns and the final filter are thermally isolated from the 2-K structure by Kevlar wires, and are cooled by a thermal strap to the ^{3}He refrigerator (see section 3.2 below). The photometer input optics are shared with the spectrometer. The separate spectrometer field of view is directed to the other side of the optical bench panel by a pick-off mirror.

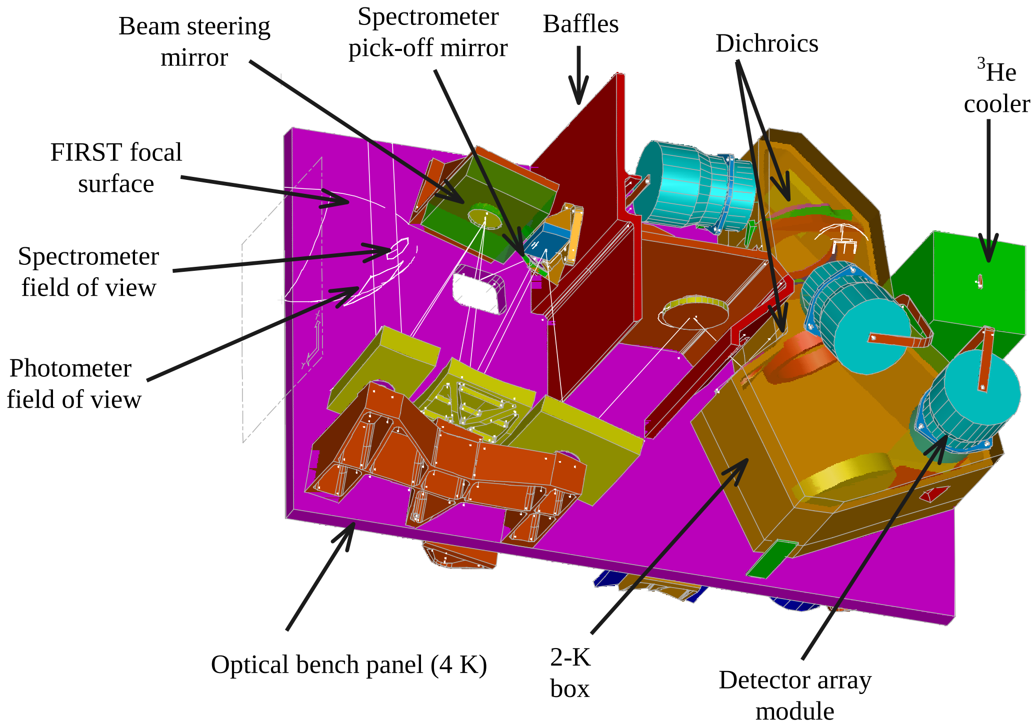

Figure 1: Computer-generated image of the imaging photometer layout.

The optical design of the photometer is shown in Fig. 2, and is described in more detail by Dohlen et al.[4] It is an all-reflective system except for two dichroic beam dividers used to direct the three wavelength bands onto different bolometer arrays, and various transmissive band-pass and edge filters used to reject out-of-band radiation. It is optimised to give close to diffraction-limited imaging across the whole 4 x 8 arcminute field of view. The SPIRE field of view is offset by 11 arcminutes from the centre of the FIRST telescope's highly curved focal surface. Mirror M3, which lies below the focus, receives the f/8.68 beam from the telescope and forms a pupil image of the telescope secondary at the flat beam steering mirror, M4. Mirror M5 converts the focal ratio to f/5 and provides an intermediate focus at the next mirror, M6, which re-images the aperture stop at M4 to a cold stop. M7, M8 and M9 constitute a one-to-one optical relay to bring the M6 focus to the three detector arrays. The beams for the three bands are directed onto the arrays at f/5 by a combination of flat folding mirrors and fixed dichroics set at 25^o to the beam axis. M3 - M8 are at 4 K and the cold stop and all subsequent optics are at 2 K.

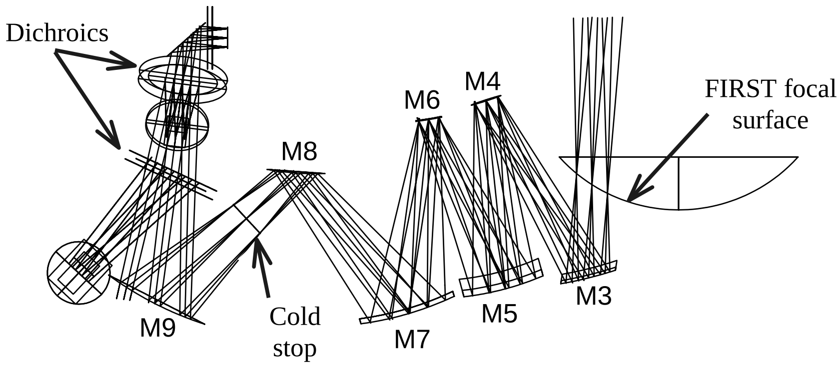

Figure 2: Imaging photometer optical design.

A shutter can be inserted to block the beam between M3 and M4. This will be important for ground testing in the FIRST cryostat where the background radiation from the cryostat shields and lid will be much greater than in flight. The shutter will allow the detector performance to be tested and verified under controlled flight-representative conditions. Flight operation of the shutter is not baselined.

An internal calibration source provides a repeatable signal for the bolometer arrays. It radiates through a 1-mm hole in the centre of the beam steering mirror, M4. As this is at a pupil image, the illumination is close to uniform over the arrays. The source can be modulated at frequencies up to 5 Hz, and operated at temperatures up to 80 K to give sufficient signal on the arrays, with peak power dissipation < 2 mW.

The beam steering mirror is capable of chopping ± 2 arcminutes along the long axis of the 4 x 8 arcminute field of view, at frequencies up to 2 Hz with an efficiency of 90% and power dissipation < 2 mW. It can operate at higher frequencies with reduced efficiency and increased power dissipation. The beam steering mechanism can simultaneously chop at up to 1 Hz in the orthogonal direction by up to 30 arcseconds. Two axis motion allows "jiggling" of the pointing to create a fully sampled image of the sky with the feedhorn-coupled detectors whose diffraction-limited beams on the sky are separated by approximately twice the beam FWHM.

The SPIRE filtering scheme is designed to provide precise definition of the spectral passbands with high out-of-band rejection and maximum in-band transmission, and also to minimise the thermal loading on the 4-K, 2-K and 0.3-K stages by reflecting short-wavelength radiation. To achieve complete rejection out to UV wavelengths, four blocking filters are needed in the chain. Figure 3 shows the measured transmission profile of a prototype 350-μm band filter set on linear and logarithmic scales. The out-of-band rejection requirements, based on the pessimistic assumption that the telescope behaves as a perfect reflector out to UV wavelengths, are easily met while maintaining a high transmission in the passband.

3.2 PHOTOMETER ARRAYS

SPIRE will use spider-web bolometers using NTD germanium thermometers[5,6]. The bolometers are coupled to the telescope by hexagonally close-packed 2Fλ-diameter single-mode conical feedhorns, providing diffraction limited beams. Modelling of the complete optical train predicts FWHM beam widths of 17.1, 24.4 and 34.6 arcseconds at 250, 350 and 500 μm respectively. The numbers of detectors in the three arrays are 149, 88, and 43 for 250, 350 and 500 μm respectively, making a total of 280

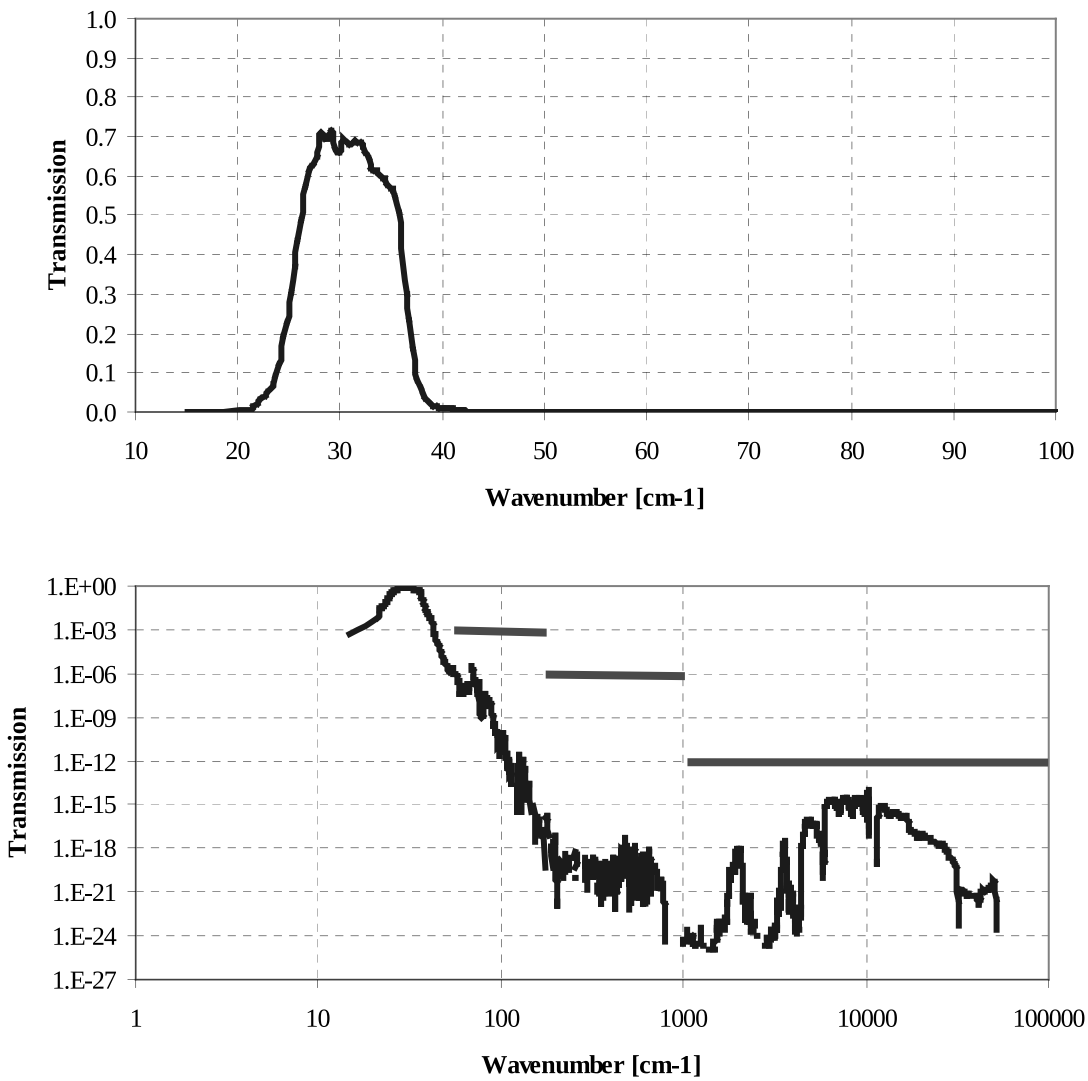

Figure 3: Prototype photometer 350-μm band filter chain transmission profile. The optical and UV transmissions of the individual elements have been measured separately and multiplied together to derive the overall transmission. The horizontal lines on the logaritmic plot indicate the out-of-band rejection requirements.

detectors for the photometer. The detector arrays are shown schematically in Fig. 4a, and a photograph of a prototype array module is shown in Fig. 4b. Each array unit has an interface to the 2-K box, with a thermal strap from the ^{3}He cooler to the 0.3-K stage, which is supported by Kevlar strings from the 2-K level. The electrical connections to the detectors are made with Kapton ribbon cable. The bolometers are excited by an AC bias at 200 Hz, which eliminates 1/f noise from the JFET readout, giving a 1/f knee for the system of less than 100 mHz. The detector NEP of ~ 3 x 10^{-17} W Hz^{-1} ensures that the overall NEP will be dominated by the thermal emission from the FIRST telescope.

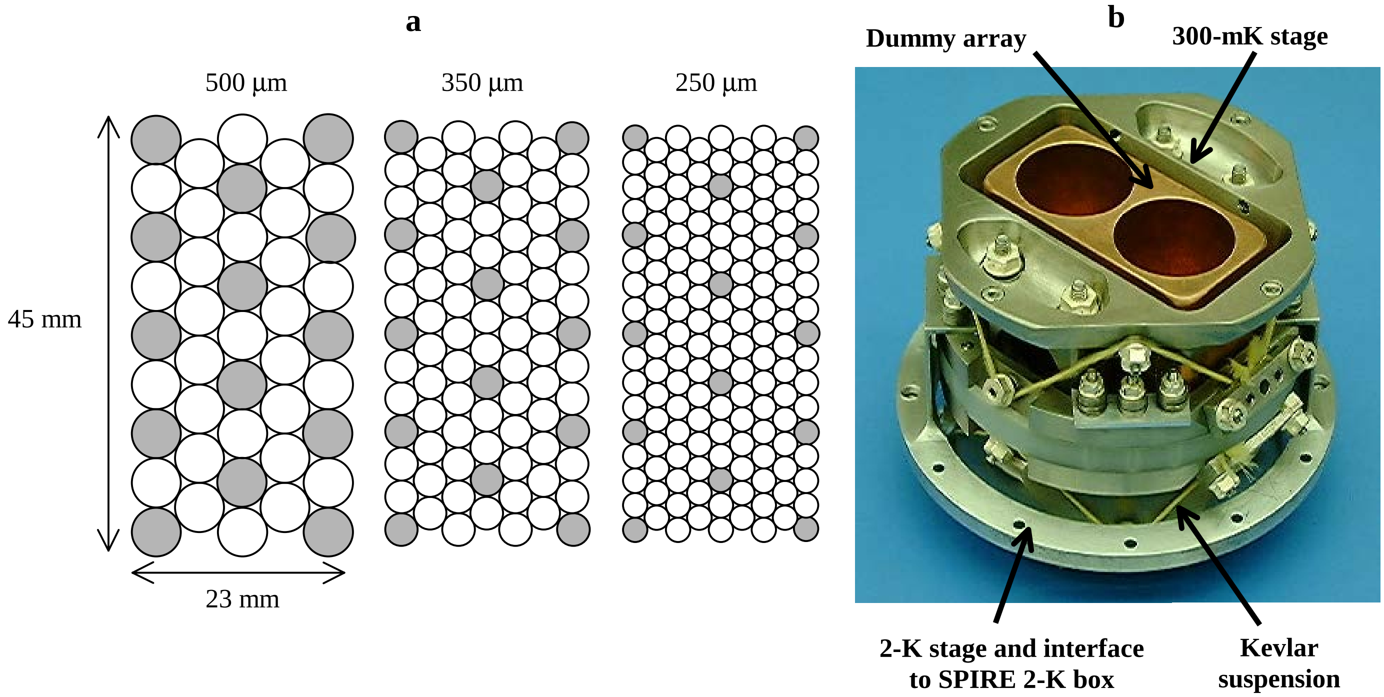

Figure 4: (a) Layout of the photometer arrays. The shaded detectors are those for which there is exact overlap on the sky for the three bands; (b) SPIRE detector array module mechanical prototype.

3.3 PHOTOMETER OBSERVING MODES

The photometer will have three principal observing modes, as described below.

Scan mapping: This mode will be used for mapping large areas of sky (much bigger than the SPIRE field of view), including deep survey observations. The telescope will be scanned across the sky (the maximum rate that the spacecraft can provide is 1 arcminute per second). Because of the excellent 1/f stability of the NTD detectors, the beam steering mirror does not need to be operated - spatial modulation is provided by the telescope motion. To provide the necessary beam overlap for full spatial sampling over the strip defined by a single scan, the scan angle must be at 14.5^{o} to one of the array axes.

Field mapping: For mapping of regions a few arcminutes in extent, the beam steering mirror will be used to carry out a jiggle map, similar to the mode of operation of the SCUBA bolometer camera on the JCMT[7]. A 64-point jiggle pattern is needed to achieve full spatial sampling in all bands simultaneously, with a step size of 9 arcseconds (half-beam spacing at 250 µm). A maximum field size of 4 x 4 arcminutes is available in this mode as one half of the array will be chopped outside the SPIRE field of view.

Point source photometry: For photometric observations of point or compact sources, chopping will be used. As shown in Fig. 4a, there are several sets of three detectors for which the beams at the three wavelengths are co-aligned on the sky. By chopping through the appropriate angle (approx. 125 arcseconds), 3-band photometric observations can be carried out simultaneously with maximum efficiency. To account for the possibility of positional errors due to telescope pointing inaccuracy or imperfect knowledge of the source position, the beam steering mirror can be used to implement a seven-point mapping routine in this mode.

The available telemetry rate of 100 kbs allows all of the 280 photometer detectors to be sampled with 16-bit resolution at up to 28 Hz and the data telemetered directly to the ground with no on-board processing (we assume an observing efficiency of 0.9).

4 FOURIER TRANSFORM SPECTROMETER

4.1 OPTICAL DESIGN AND FPU LAYOUT

The focal plane layout of the Fourier Transform spectrometer is shown in Fig. 5 and the optical design is illustrated in Fig. 6.

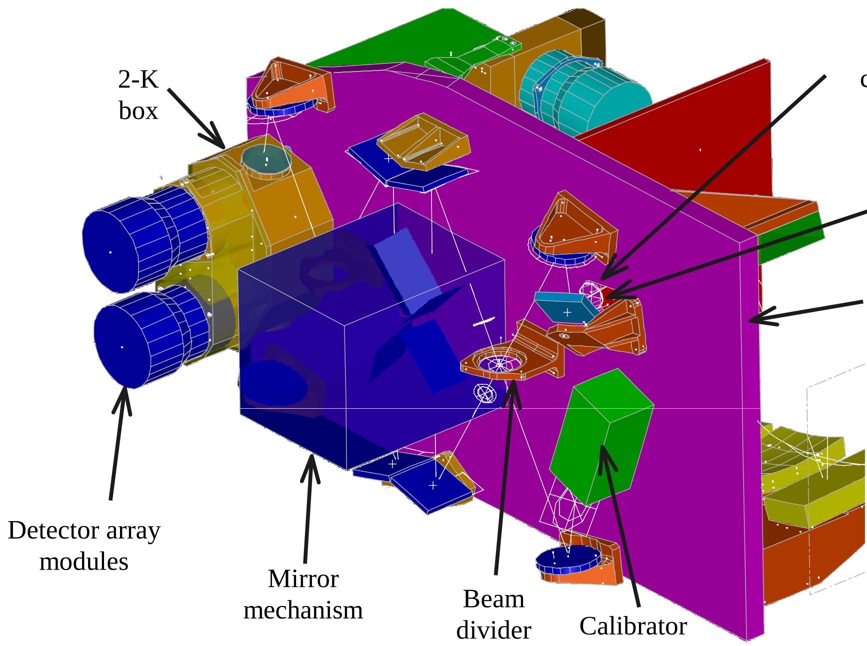

Figure 5: Computer-generated image of the SPIRE FTS layout. The FTS mechanism and the majority of its optics are mounted on the 4-K optical bench panel.

The FTS[8] uses two broadband, high-efficiency, intensity beam splitters in a Mach-Zehnder configuration rather than the traditional polarising beam dividers. This configuration has the advantage that all four ports are separately accessible, as in the classical Martin Puplett (M-P) polarising FTS. But the throughput is a factor of two higher than for the M-P as none of the incoming radiation is rejected, and there is no sensitivity to the polarisation of the incident radiation. The performance of the beam dividers and of a bench-top implementation of this design has been demonstrated[9]. A thermal calibrator is located at a pupil image in the second input port of the FTS, and provides a thermal spectrum that mimics the dilute 80-K black body emission spectrum of the telescope. This allows the large telescope background to be nulled, thereby reducing the dynamic range requirements for the detector sampling. Two band-limited detector arrays are placed in the two output ports, covering 200-300 µm and 300-670 µm. A single back-to-back moving roof-top mechanism serves both arms of the interferometer, with a frictionless carriage mechanism using double parallelogram linkage and flex pivots.

The pick-off mirror (on the photometer side of the optical bench panel and located at the intermediate field image) directs the spectrometer field of view through a hole in the optical bench panel into the FTS side of the instrument. A 4-K pupil stop is located between the pick-off mirror and the input fold mirror. The input relay mirror focuses the beam to intermediate image

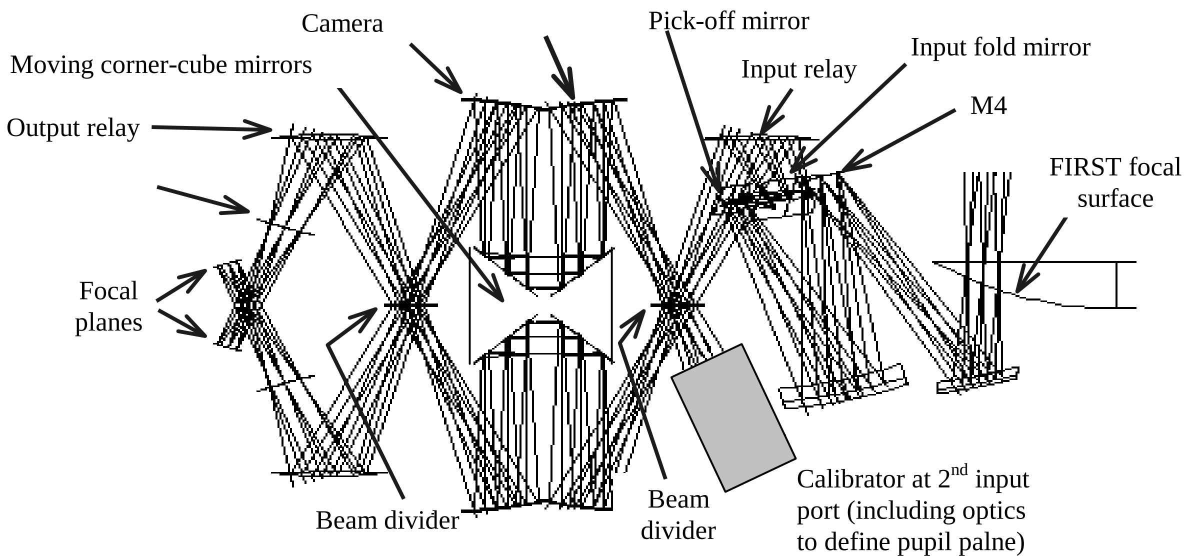

Figure 6: Optical design of the imaging FTS.

plane located just after the first beam divider, after which the beam is collimated sent to the moving corner cube assembly. The corner cube shifts the beam and sends it towards the camera mirror, which produces an image plane just before the output beam divider. The output relay mirror focuses the beam onto the detector arrays. A pupil image is located near the final fold mirror, making this a convenient location for the entrance aperture to the 2K enclosure. As this pupil moves when the optical path difference changes, it is not a good place for a limiting cold stop. Instead, the limiting aperture is located at the 4-K pupil plane between the pick-off mirror and the input fold mirror.

The FTS design is optimised for the 200-400 μm band. The wavelength coverage is extended to 15 cm^{-1} (670 μm) to give access to the astrophysically important 609-μm line of CI in our own and nearby galaxies, and to extend the range over which the spectral energy distribution of sources can be measured in the FTS low-resolution mode. A filtering scheme similar to the one employed for the photometer channel is used to restrict the passband of the instrument. Filters on the bolometer arrays themselves define the passband for each array.

4.2 SPECTROMETER ARRAYS

The field of view of the FTS is approximately 2.6 arcminutes in diameter, and is covered by 37 hexagonally close-packed detectors in the short-wavelength array and 19 in the long-wavelength array. The detector modules will be similar to those used for the photometer, with a mechanical interface to the wall of the 2-K enclosure.

The two FTS arrays cover the 200-300 and 300-670 μm bands. The detectors and feedhorns for the short wavelength band are similar to those for the photometer 250 μm channel. The long wavelength band is optimised for the 300-400 μm range, with the feedhorn aperture equal to 2Fλ at 350 μm, but some compromises are essential to achieve the necessary broad-band performance. There is a factor of two loss in point source coupling efficiency at the longest wavelengths due to the smaller aperture relative to the wavelength. The waveguide coupling the horn to the bolometer must also have a diameter large enough to transmit at 670 μm, and so is overmoded at the shorter wavelengths within the band. This results in an increase in background radiation on the detectors and a broadening of the beam by about 20% compared to the diffraction limit at the lower end of the band[10].

4.3 SPECTROMETER OPERATING MODES

The FTS will be operated in continuous scan mode with the mirrors moving at a constant speed of 0.1 cm s^{-1}, corresponding to a signal frequency range of 6 – 20 Hz. The spectral resolution can be adjusted between 0.04 and 2 cm^{-1} ($\lambda/\Delta\lambda$ = 1000 – 20 at 250 μm). The maximum scan length is 3.5 cm (taking 35 seconds and giving an optical path difference of 14 cm). To ensure that mechanism jitter noise is well below the photon noise level, a relative accuracy of 0.1 μm is required for the mirror position. The FTS calibration source will be on continuously while the spectrometer is operating, with a peak power of no more than 5 mW. For spectral mapping of extended sources, the beam steering mirror will be used to provide the necessary pointing changes between scans.

The scanning mirror control system uses a digital feedback loop to provide a constant speed over the scan length, with an accuracy requirement of 1% (goal 0.5%). The position readout uses a Heidenhain Moiré fringe sensing system. The detectors are read out asynchronously with the samples time-stamped to match them to the corresponding mirror locations. No on-board processing will be done - the raw interferograms will be telemetered to the ground. The number of detectors and the available telemetry rate are compatible with an oversampling factor of 2.5 with respect to the Nyquist sampling rate of 40 Hz (sampling at approx. 100 Hz per detector). An oversampling factor somewhat greater than this is desirable - options to achieve this include increasing the data rate, decreasing the mirror speed, sampling only a fraction of the detectors in some cases (e.g., point source observations), or a combination of these.

5 ^{3}He COOLER

The ^{3}He cooler[11] uses porous material to adsorb or release a gas when cooled or heated. This type of refrigerator is well-suited to a space environment. Gas gap heat switches are used the control the refrigerator and there are no moving parts. It can be recycled indefinitely with over 95% duty cycle efficiency and the lifetime is only limited by that of the cold stage from which it is run (in this case, the lifetime of the FIRST cryostat). The evaporation of ^{3}He naturally provides a very stable operating temperature under constant heat load over the entire cycle. The cooler requires no mechanical or vacuum connections and only low-current electrical leads for its operation, making the mechanical and electrical interfaces very simple. For operation in a zero-g environment two aspects of the design of a ^{3}He refrigerator have been addressed: the liquid confinement and the structural strength required for the launch. The confinement within the evaporator is provided by a porous material which holds the liquid by capillary attraction. For the thermal isolation and structural support of the refrigerator elements, a suspension system using Kevlar wires has been designed to support the cooler firmly during launch whilst minimising the parasitic heat load on the system. The base-line SPIRE cooler contains 4 STP litres of ^{3}He, fits in a 200 x 100 x100 mm envelope and weighs about 0.5 kg. Its performance has been analysed using the same methods that successfully predicted the performance of the IRTS cooler on orbit. When operated from a 1.8-K heat sink it achieves a temperature of 274 mK at the evaporator with a 10-μW load on the evaporator, a hold time of 46 hours and a duty cycle efficiency of 96%. The total time-averaged power load on the 1.7 K heat sink is approximately 3 mW. The ^{3}He cooler is a potential single point failure for the instrument. Its reliability and redundancy are under analysis, and an option with double parallel heat switches is being considered.

6 PERFORMANCE ESTIMATION

The sensitivity of SPIRE has been estimated under the assumptions listed below. Pessimistic overall optical efficiencies of 30% for the photometer and 15% for the FTS are assumed, taking into account all losses including filter transmission, mirror reflectivity, diffraction within the instrument and pupil alignment errors.

Telescope:	Temperature	80 K
	Used diameter	3.29 m (secondary mirror is pupil stop)
	Emissivity	0.04

Detectors:	Bolometer optical NEP	3.0 x 10^{-17} W $Hz^{-1/2}$
	Bolometer quantum efficiency	0.8
	Bolometer feed-horn efficiency	0.7
	Throughput for each pixel	$A\Omega = \lambda^2$ (2.0Fλ feed-horns)
Photometer:	Central wavelengths	250 350 and 500 µm
	Numbers of pixels	149 88 and 43
	Beam FWHM	17.4 24.4 and 34.6 arcseconds
	Field of view of each array	4 x 8 arcminutes
	Overall instrument transmission	30%
	Filter widths ($\lambda/\Delta\lambda$)	3
	Observing efficiency	90%
FTS spectrometer:	Nominal bands	33.5-50 cm^{-1} (200-300 µm) 15-33.5 cm^{-1} (300-670 µm)
	Numbers of pixels	37 19
	Field of view	2.6 arcminutes, approx. circular
	Max. spectral resolution	0.04 cm^{-1} ($\lambda/\Delta\lambda$ = 1000 at 250 µm)
	Overall instrument transmission	15%
	Cos^2 signal modulation efficiency	0.5
	Observing efficiency	0.8
	Electrical filter efficiency	0.8

The background power levels on the detectors (which are dominated by the telescope emission), and the corresponding photon noise limited NEP values are given in Table 1.

		Photometer band			FTS band	
		250 µm	350 µm	500 µm	200–300 µm	300–670 µm
Background power/detector	pW	5.1	4.0	3.1	8.8	25
Background-limited NEP	W $Hz^{-1/2}$ x 10^{-17}	9.1	6.5	5.1	14	17

Table 1: Background power and photon noise-limited NEPs for SPIRE.

The instrument sensitivity is summarised in Table 2. The extragalactic confusion limit for SPIRE is in the region of 10-20 mJy (depending on the wavelength, the adopted source count models, and how one chooses to define the confusion limit). The photometer is thus capable of integrating down to the FIRST confusion limit with a sensitivity of 5 σ in a matter of minutes. This will allow large area confusion-limited deep surveys to be carried out at a rate on the order of one degree per day. The FTS will be used to follow up brighter sources from this survey (and other existing catalogues) to determine the SEDs and carry out spectral line surveys with simultaneous coverage of the 200 - 670 µm band.

Photometry					
λ	μm		250	350	500
ΔS (1σ; 1 hr)	mJy	Point source	0.48	0.53	0.59
		4' x 8' map	1.1	1.2	1.5

Line spectroscopy $\Delta\sigma = 0.04$ cm^{-1}				
λ μm		200	400	670
ΔS (1σ; 1 hr) W m^{-2} x 10^{-18}	Point source	5.4	6.9	14
	2.6' map	13	16	32

Low-resolution spectrophotometry $\Delta\sigma = 1$ cm^{-1}					
λ	μm		200	400	670
ΔS (1σ; 1 hr)	mJy	Point source	18	23	46
		2.6' map	44	53	106

Table 2: Estimated sensitivity of SPIRE for broad-band photometry, line spectroscopy and low-resolution spectrophotometry.

7 THE SPIRE CONSORTIUM

SPIRE is being built by a consortium of European, American and Canadian scientists from the following groups: Caltech/Jet Propulsion Laboratory, Pasadena; CEA Service d'Astrophysique, Saclay, France; Institut d'Astrophysique Spatiale, Orsay, France; Imperial College, London, UK; Instituto de Astrofisica de Canarias, Tenerife, Spain; Istituto di Fisica dello Spazio Interplanetario, Rome, Italy; Laboratoire d'Astronomie Spatiale, Marseille; Mullard Space Science Laboratory, Surrey, UK; NASA Goddard Space Flight Center, Maryland, USA; Observatoire de Paris, Meudon, Paris; Queen Mary and Westfield College, London, UK; UK Astronomy Technology Centre, Edinburgh, UK; Rutherford Appleton Laboratory, Oxfordshire, UK; Stockholm Observatory, Sweden; Università di Padova, Italy; University of Saskatchewan, Canada.

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