SPIRE - a bolometer instrument for FIRST

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ABSTRACT

The European Space Agency's FIRST satellite will include a submillimetre direct detection instrument using bolometric detectors. The scientific drivers for the instrument are discussed and the essential features of the proposed instrument, SPIRE, are described. SPIRE (Spectral and Photometric Imaging REceiver) comprises a three-band imaging photometer covering the 250-500-μm range and an imaging Fourier Transform Spectrometer covering wavelengths between 200 and 670 μm. The SPIRE detectors are 300-mK bolometer arrays providing full sampling of the diffraction spot. The imaging photometer is optimised for deep photometric surveys in the submillimetre (one of the main science goals of the FIRST mission), for which application it will be much more sensitive than any Earth-based facility. The nominal bands for the photometer are 250, 350 and 500 μm with a spectral resolution of 3. Three detector arrays observe the same 4-arcminute field of view simultaneously, with dichroic beam dividers separating the bands. The imaging spectrometer has a 2-arcminute field of view and an adjustable spectral resolution of 0.04 - 2 cm^{-1} ($\lambda/\Delta\lambda$ = 20 - 1000 at 250 μm).

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

1 INTRODUCTION

SPIRE (Spectral and Photometric Imaging REceiver) is one of the three focal plane instruments proposed for ESA's FIRST mission[1]. It is designed primarily to exploit FIRST's unique capabilities in addressing two of the most prominent questions of modern astrophysics:

(i) the investigation of the statistics and physics of galaxy and structure formation at high redshift;
(ii) the study of the earliest stages of star formation, when the protostar is still coupled to the interstellar medium.

These investigations require the ability to carry out large-area 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 unique advantages of FIRST, which cannot be matched by any other facilities: its large-aperture, cold, low-emissivity telescope; the complete lack of atmospheric emission 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 photometry and moderate-resolution spectroscopy.

Galaxies emit a large fraction (from 30% to nearly 100%) of their energy in the far infrared due to re-processing of stellar UV radiation by interstellar dust. The far infrared peak is redshifted into the SPIRE wavelength domain for galaxies with redshift, z, greater than ~ 1. The bolometric 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.

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

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the stellar initial mass function (IMF). Sensitive far infrared and submillimetre observations with high spatial resolution are necessary to 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 to study the behavior of the interstellar gas and dust prior to 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 mass - 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, 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 a detailed SEDs of selected objects and measure key spectral lines. Many objects will be faint compared to the sky background, and accurate subtraction of the background must be performed. These scientific requirements have been important in the choice of a Fourier Transform Spectrometer over the grating spectrometer previously proposed for this instrument. The grating, whilst well adapted to observations of known lines, has the disadvantages that its fixed spectral resolution is unsuitable for the faintest objects detected in the photometric surveys, and that it does not naturally lend itself to providing an imaging capability.

Although SPIRE has been optimised for these two main scientific programmes, it will offer the astronomical community unique capabilities to tackle many other astrophysical problems: 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.

2 INSTRUMENT OVERVIEW

SPIRE comprises an imaging photometer and an imaging Fourier Transform Spectrometer (FTS). The photometer has a 4-arcminute field of view (the maximum possible given the constraints of the FIRST focal plane layout). Three imaging arrays of bolometers provide broad-band photometry ($\lambda/\Delta\lambda \approx 3$) in wavelength bands centred on 250, 350 and 500 μm. The instrument does not use a filter wheel: the whole field of view is observed simultaneously in all bands through the use of fixed dichroic beam-splitters. Sky chopping is provided by a chopping mirror within the instrument (this is the only mechanism within the photometer). An internal thermal calibration source is available to provide a repeatable calibration signal for the detectors. The FTS uses the Martin Puplett[2] polarising design, which has two input and two output ports. One input port covers a 2-arcminute 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 of the FTS is determined by the maximum optical path difference for a scan, and will be adjustable between 0.04 and 2 cm^{-1} (which corresponds to $\lambda/\Delta\lambda = 20 - 1000$ at 250 μm wavelength). The photometer and spectrometer are not designed to operate simultaneously.

After a detailed study, the FTS was chosen in favour of the previous grating design[3] for a number of reasons.

(i) The FTS fully utilises the imaging capabilities of the FIRST telescope, which was not possible with the grating.
(ii) The spectral resolution can easily be adjusted and tailored to the scientific requirements of the observation.
(iii) The detectors can be operated at 300 mK because the photon noise limited NEP is higher for the FTS, whose detectors observe broad-band, than for grating or Fabry Perot spectrometers in which they observe in narrow-band mode. This allows a ^{3}He sorption cooler to be adopted for SPIRE - a considerable simplification over the previously base-lined dilution cooler.
(iv) Whilst the grating is more sensitive, at least in principle, for observations of known spectral lines, there is little difference in the sensitivities of the two options for spectral survey observations, which are of greater scientific priority for SPIRE.
(v) The FTS is less vulnerable to degradation in performance arising from stray light and out-of-band leaks which can be problematic with a low-background grating instrument.

The base-line detectors for SPIRE are planar bolometer arrays (without feed-horns) providing full instantaneous sampling of the telescope point spread function. Several different types of detector array and associated cold multiplexer are currently under development within the SPIRE consortium, and the best has yet to be selected. A proven fall-back option, incorporating the technique of feed-horn arrays (as used by the successful SCUBA instrument[4] on the JCMT telescope) is available should there be any major difficulties with the planar bolometer array technology.

The SPIRE ^{3}He cooler is similar in its essential features to the one successfully flown in 1995 on the Japanese IRTS satellite. It is a self-contained unit with simple electrical and mechanical interfaces to the spacecraft, and is designed specifically for the requirements of SPIRE and FIRST.

The large numbers of pixels in both the spectrometer and photometer requires a significant amount of on-board signal processing to accommodate the available telemetry rate (< 60 kbits/s). A specialised signal processing unit will carry out data de-spiking and signal averaging (of both photometric frames and spectrometer interferograms) prior to transmission of the data to the ground.

3 FOCAL PLANE UNIT

The focal plane unit consists of four separate enclosures at nominal temperatures of 9, 4, 1.7 K (all provided by the FIRST cryostat) and 300 mK (provided by SPIRE's internal cooler). Each enclosure is located within the next higher temperature enclosure. The main interface to the cryostat is at the 9-K level. The 4-K and 2-K boxes will be supported from 9 K by Carbon Fibre Reinforced Plastic (CFRP) struts and titanium mounts. The photometer and spectrometer share some input optics, and their detector arrays are served by the same ^{3}He cooler, but otherwise they occupy separate compartments within the FPU. Each contains optical elements at 2 K and 4 K. The optical designs of both parts of the instrument will be carefully optimised for maximum stray light rejection and minimum aberrations. Three-dimensional views of the cold focal plane unit are shown in Figs. 1 and 2.

3.1 ^{3}He COOLER

The ^{3}He sorption cooler uses porous material to adsorb or release a gas when cooled or heated. This type of refrigerator is well-suited to a space environment[5]. Gas gap heat switches[6] 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 connections 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 with an 8-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 1.8 K heat sink is 2.4 mW.

3.2 IMAGING PHOTOMETER

The optical design of the photometer is shown in Fig. 3. It is an all-reflective system except for two dichroic beam splitters used to split the three wavelength bands onto different bolometer arrays, and various transmissive band-pass filters used to

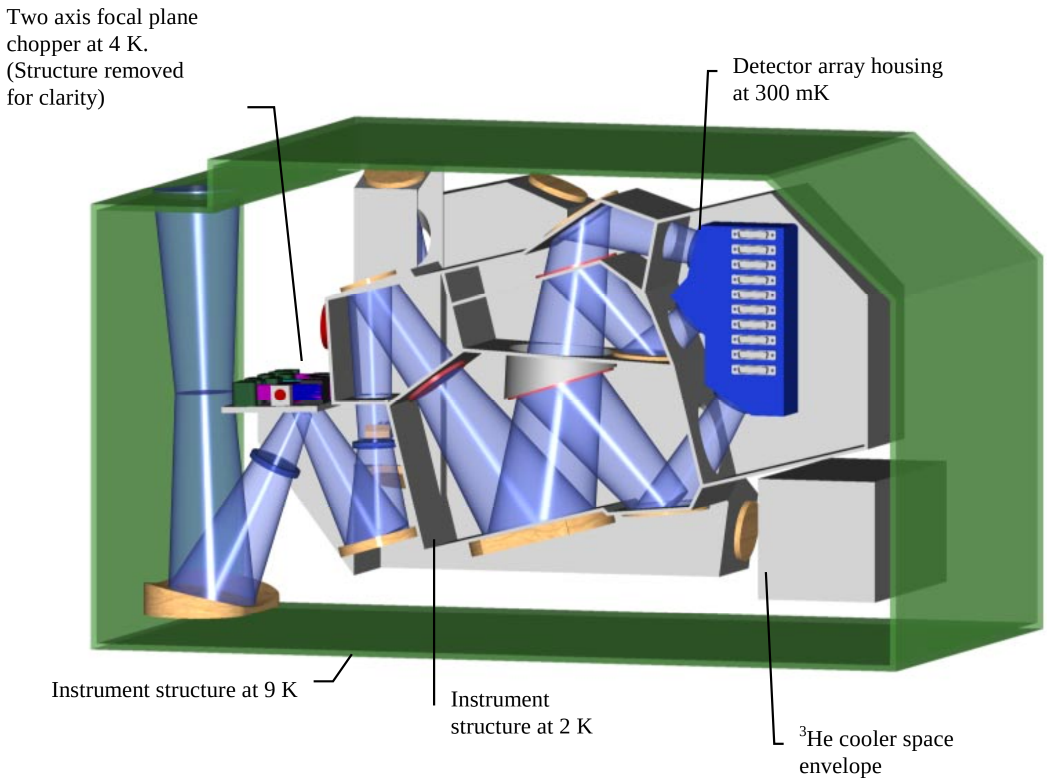

Figure 1: Computer-generated image of SPIRE viewed from the photometer channel side of the instrument.

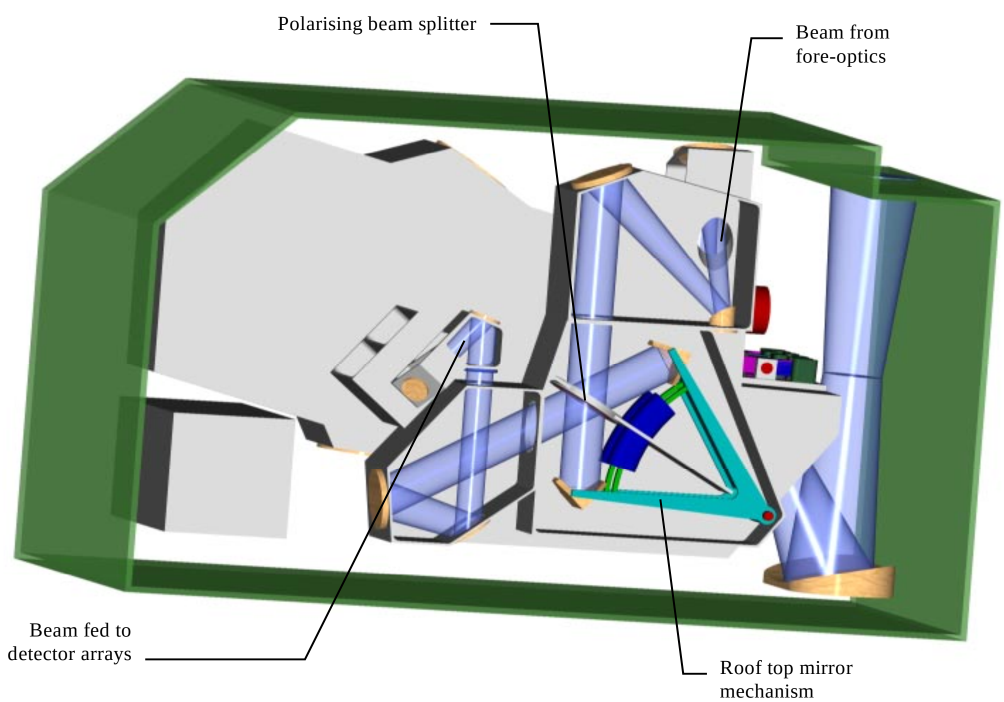

Figure 2: Computer-generated image of SPIRE viewed from the FTS side of the instrument. The FTS mechanism and the majority of its optics will be mounted on the 4-K structure.

reject out-of-band radiation. The first mirror, M3, is spherical and has a 170-mm focal length. It receives the f/8.68 beam from the telescope and forms a pupil image of the telescope secondary at the flat chopping mirror, M4, which is designed to give a maximum $\pm$ 3.7^o chop angle, corresponding to 5 arcminutes on the sky. The next mirror, M5, is toroidal and re-images the focal plane at f/4.5 defining a convenient field stop at 2 K. It also re-images the aperture stop at the chopper to a physical cold stop at 2 K. The last powered mirror, M7, is also toroidal and presents an f/5 beam to the detectors. The beams for the three bands are directed onto the bolometer arrays by a combination of flat folding mirrors and fixed dichroics set at 25^o to the beam axis. The optical design is optimised to give close to diffraction-limited imaging across the whole field of view whilst minimising the pupil image aberrations.

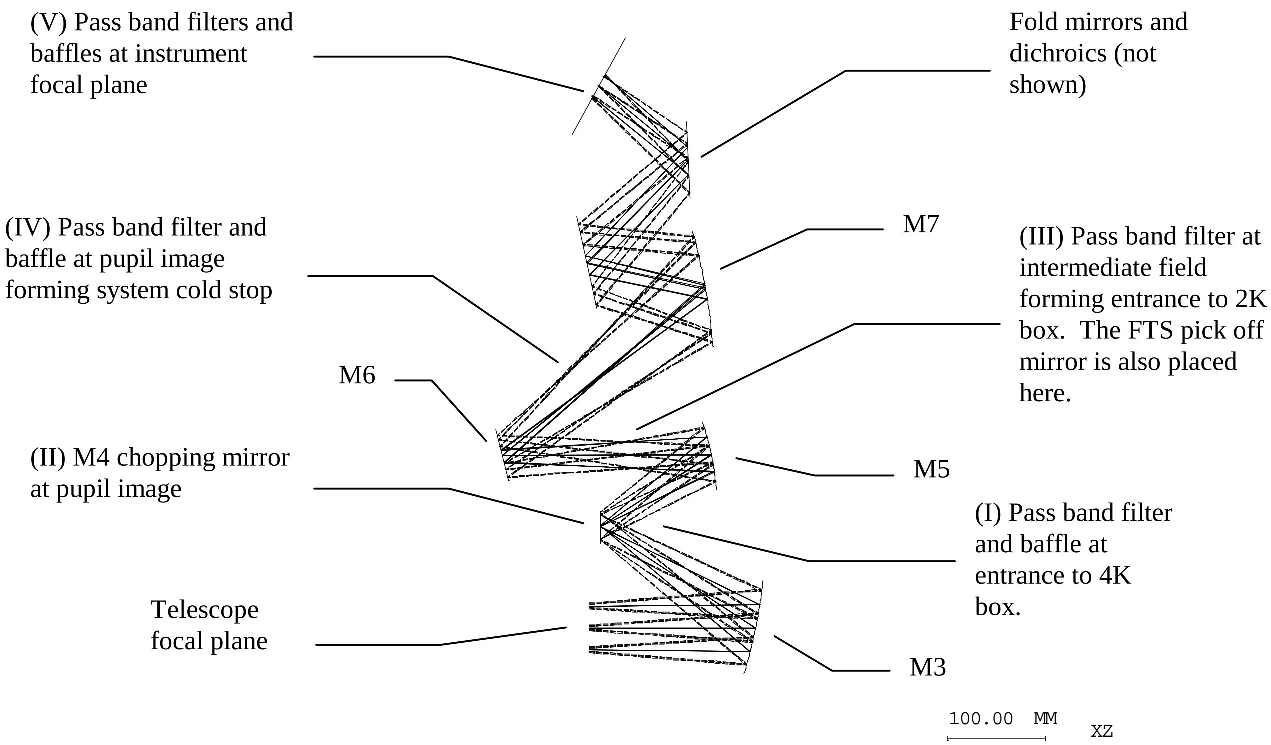

Figure 3: Optical layout of the photometer showing the positions of the stray-light control filters and baffles.

An internal calibration source will provide a repeatable signal for the bolometer arrays. It will be located at a hole through the centre of the focal plane chopper (at a pupil image, coincident with the image of the central obscuration of the telescope). The source will be mechanically and thermally interfaced to the 4-K structure. It will be operated at temperatures up to 25 K to give sufficient power on the arrays. The peak power dissipation will be around 2 mW with a duty cycle of < 5%.

Radiation at any wavelength can be detected by the bolometer arrays. Therefore, the control of thermal emission from warm parts of the instrument and spacecraft structure, and also of any out-of-band radiation from celestial sources, will be crucial to the sensitivity and proper calibration of the instrument. With no feed-horns, the arrays will have a wide intrinsic field of view and the filtering and baffling throughout the instrument will be carefully designed to ensure that they only see cold parts of the structure (< 4 K) which will not contribute significantly over the background from the low-emissivity 80-K telescope. Several methods of rejecting unwanted radiation will be employed: the use of several structural elements at successively lower temperatures; cold stops that are undersized with respect to the telescope pupil placed at the 4-K chopper and the 2-K aperture image (positions II and IV in Fig. 3); edge filters placed at strategic points in the optical train to control the thermal environment within each box and reject out of band radiation (positions I, III and IV in Fig. 3); physical baffling to control out of field radiation (positions I, IV and V in Fig. 3) and band-pass filters placed close to the bolometer arrays to define the wavelength band each array sees. In addition, care will be exercised in the design and construction of the instrument to ensure that there are no un-baffled holes through which unwanted radiation can enter the system (vent holes, cable feed-throughs and cold straps will all be baffled).

3.3 FOURIER TRANSFORM SPECTROMETER

The base-line layout for the FTS is shown in Fig. 4. A pick off mirror, PO, is placed at the intermediate field image (position III in Fig. 3) and sends the beam via a folding flat, R1, to a collimating mirror R2. An image of the pupil is formed between R2 and R3 and the input polariser can be placed here. This has the advantage that the second input port is also a pupil image as seen from the detectors and a calibration source placed here will be superimposed on the input signal from the telescope. Mirror R3 forms an intermediate field image at F which is then re-collimated by the mirror COLL and sent towards the beam-splitter and roof-top mirrors at BS, RT1 and RT2. The roof top mirrors are mounted on a swinging arm in this design and both of them move; this gives a folding factor of four between the actual mirror movement and the effective change in the optical path difference. The output beam of the FTS is re-imaged by the camera mirrors CAM1 and CAM2. The output polariser OP splits the beam between two arrays with band-pass filtering designed to give approximately equal power from the telescope on each array.

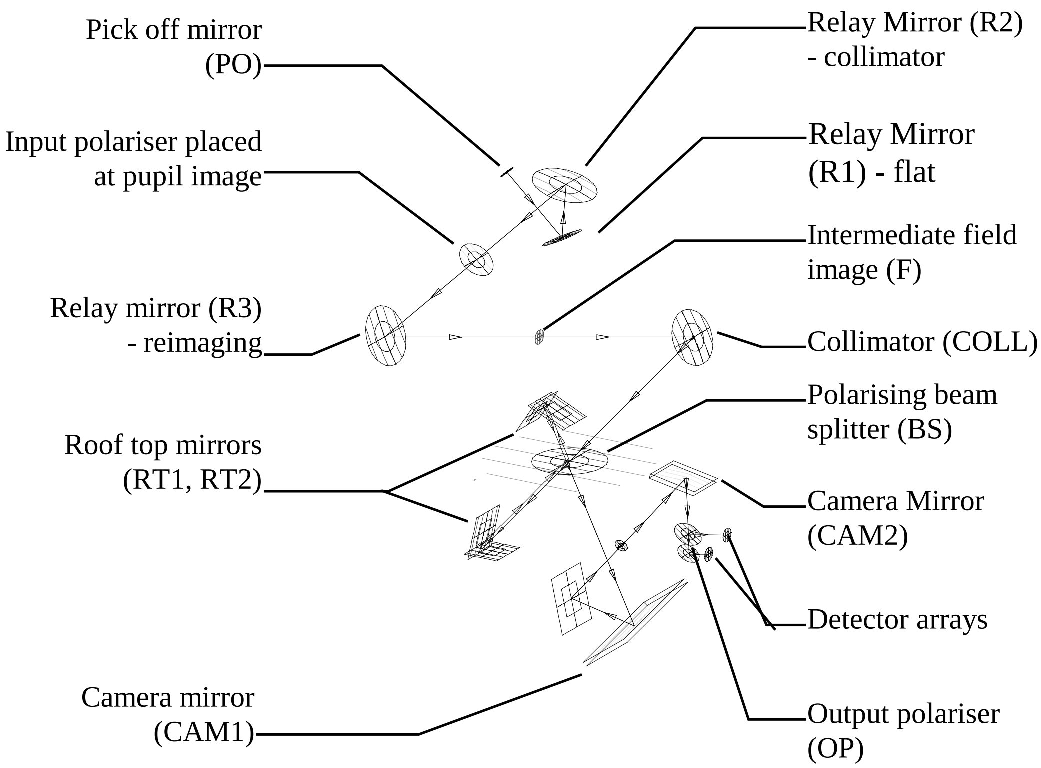

Figure 4: Optical layout of the FTS spectrometer.

Calculations of the effect of beam shear and loss of coherence across the interfering beams show that a 30-mm beam diameter is required to prevent significant loss of resolution at the edges of a 2 x 2 arcminute field of view. The optical design is optimised to give close to diffraction-limited imaging at all points in the field of view.

The moving mirror scheme in this design involves the use of a linear motor and measurement system mounted on a curved track. An alternative design is also being considered which uses a single moving fold mirror and two fixed roof-top mirrors. This has the benefit of using a directly linear motion whilst maintaining the folding factor of four, possibly at the expense of a more bulky instrument. 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} ($\lambda/\Delta\lambda$ = 20 – 1000 at 250 μm). The maximum scan length is 3.5 cm (giving an optical path difference of 14 cm). The requirement to average spectral scans on-board before sending the data to the ground dictates that the FTS mechanism position be highly reproducible from one scan to another. An initial study shows this repeatability requirement to be of the order of 0.1 µm.

The FTS internal calibrator at the second port will be a thermal source placed at the pupil image before the input polariser and interfaced to the 4-K structure. Placing the source at this position with a suitable feed horn arrangement will ensure that all parts of the imaged field of view will receive the same amount of power from the calibration source. In order to null the dilute 80-K radiation from the telescope it will be necessary to run the source at up to 40 K. The calibration source will be on continuously while the FTS is operating. The peak power required will be no more than 5 mW with a total duty cycle of 50% (assuming 50:50 photometer/spectrometer observation time) - an average of 2.5 mW.

A filtering scheme similar to the one employed for the photometer channel will be used to restrict the pass-band of the instrument. It will share the 4-K filter at position I in Fig. 3 with the photometer channel. A filter will also be placed at the instrument cold stop formed by the camera mirrors within the 2-K box. Filters on the bolometer arrays themselves will define the pass-band for each array. Direct baffling at critical points will restrict the field of view of the bolometer arrays and ensure strong attenuation for all radiation not coming in via the optical train.

The FTS design is optimised for the 200-400-µm band. The wavelength coverage is extended to 15 cm^{-1} (670 µm) because:

(i) there is little penalty in terms of performance over the priority 200-400-µm range;
(ii) this gives access to the astrophysically important 609-µm line of CI in our own and nearby galaxies;
(iii) it extends the range over which the spectral energy distribution of sources can be measured in the FTS low-resolution mode.

The FTS bands have been chosen to give roughly equal background power in the two bands and to make the pixel size optimum for wavelengths of 250 and 350 µm, so that arrays identical to those in the two shortest wavelength photometer bands can be used. Conveniently, a cross-over wavelength near 300 µm satisfies both of these requirements at the same time. For wavelengths longer than 400 µm, the pixel size of the long-wavelength channel will be increasingly mis-matched to the diffraction spot size. In addition, diffraction within the FTS will result in a loss of efficiency at the longest wavelengths. The implications for sensitivity of the FTS at wavelengths longward of 400 µm must be studied in detail. At present, we estimate a loss of S/N of a factor of 2 at 670 µm, and scale linearly for wavelengths between 400 and 670 µm.

3.4 DETECTOR ARRAYS

The thermal background on the detectors is dominated by the emission from the telescope. The photon noise limited NEP is around 3×10^{-17} W Hz^{-1}. The speed of response requirements are 5-Hz 3-dB frequency for the photometer arrays and 15-20 Hz for the FTS arrays.

The SPIRE base-line design employs planar arrays of bolometers without feed-horns in preference to the more traditional feed-horn fed bolometer arrays as used in SCUBA and other ground-based instruments. Analysis of the potential advantages of filled absorber arrays has shown that, for mapping observations, an improvement in observing speed by a factor of approximately 3 can be achieved. In addition, filled arrays offer a number of important practical advantages:

(i) for a point source, the observation is insensitive to any inaccuracies in the telescope pointing or in the co-ordinates of the source;
(ii) the telescope point spread function is fully sampled and the background around the source is completely characterised;
(iii) for mapping observations, the field is fully sampled instantaneously, whereas with the feed-horn option multiple pointings (a “jiggle” map) using the internal chopping mirror are necessary for full sampling of the frame. This requires around one minute at minimum for photometry, making the data more vulnerable to 1/f noise and other instabilities in the complete system;
(iv) the chopper mechanism is simplified as two-axis motion is not required;
(v) there is no need to co-align accurately three separate pixels on the three arrays in order to do simultaneous point source photometry.

The three photometer channels uses planar bolometer arrays of size 32 x 32 (250 µm), 24 x 24 (350 µm) and 16 x 16 (500 µm). The pixel size is 0.5Fλ square (where F is the final optics focal ratio) in order to sample fully the field of view. The FTS will use one 16 x 16 array for the 200-300-µm channel and one 12 x 12 array for the 300-670-µm channel.

Three basic types of planar bolometer arrays are currently under development for possible inclusion in SPIRE:

(i) spider web bolometer arrays constructed from silicon nitride with transition edge super-conducting (TES) thermistor read-out: the spider web bolometers are under development at JPL/Caltech and TES thermistors and SQUID multiplexers are being developed by GSFC and NIST, Boulder;
(ii) silicon pop-up detectors (SPUDs) with TES thermistor read-out: the SPUD bolometers are under development by GSFC and the TES technology is the same as for the spider web bolometers;
(iii) silicon grids with resonant absorbers and implanted thermometer bridge read-out with cold CMOS multiplexers: these arrays are under development by CEA, Saclay and LIR, Grenoble.

All three developments make use of micro-machined silicon or silicon nitride to produce absorbers that have a high absorption efficiency for submillimetre radiation but a low physical cross section to reduce the impact of cosmic rays.

Individual spider web bolometers with NTD germanium thermometers and cold JFET amplifiers now constitute a well-established technology for ground-based telescopes and balloon experiments[7] (and have been base-lined for the Planck HFI instrument). An array of 151 such bolometers, with straight-sided feed-horns, is currently under development for the CSO telescope. For arrays of many hundreds pixels as in SPIRE, it not be feasible to have so many JFETs close to the focal plane owing to their high thermal dissipation and the fact that they must operate at around 120 K. Therefore, even for this type of technology, a novel read out scheme is required. In the case of the spider webs[8] and SPUDs this will be the use of TES thermistors with Superconducting QUantum Interference Device (SQUID) readouts. TES devices[9,10] have a fast time response, and the limiting time response of the bolometer as a whole will be the thermalisation time of the absorber - for a spider web type absorber this will be about 1 ms. A biasing arrangement is employed whereby, via electrothermal feedback, the temperature of the device remains constant and the current passing through it changes with the incident power. The low TES resistance requires the use a SQUID readout to measure the current and SQUID multiplexers to read out the signals from multi-pixel arrays.

The SPUD bolometer array development programme is aimed at providing large format filled arrays with easy access to the output wiring whilst controlling the thermal conductivity between the heat sink and the absorber[11]. SPUD technology will also allow the use of resonant cavities behind the absorber to ensure maximum absorption and, to some extent, tune the wavelength response of the bolometer. Engineering model arrays have been built and tested with full area absorbers and the more conventional implanted silicon thermometers. For SPIRE it is planned to develop micromesh absorbers similar in concept to the spider web bolometers and to have TES/SQUID readouts.

The CEA/LIR resonant absorber arrays use micro-machined silicon grids suspended at a 1/4 wavelength distance above a substrate with a reflecting surface coating by an indium bump-bonding technique. The absorption characteristics of such a device have been modeled with a 3-D Maxwellian code which shows that it is possible to tune the arrays to have a high absorption coefficient over a 200-250-µm bandwidth around the central wavelength (this also holds for SPUD type arrays with resonant cavities as well). The temperature rise in the absorber is measured with reference to the substrate using a thermometer bridge technique. Thermometers are placed in the central part of the absorbing grid and in the substrate by the direct implantation of phosphorous into the silicon with 50% boron compensation. The thermometers will have a high impedance to allow cold CMOS-based read-out electronics to be used. Engineering model thermometers have been built and electrically tested and shown to have electrical NEPs ~ 3×10^{-17} W $Hz^{-1/2}$. Cold CMOS read-outs with amplifiers and 8-to-1 multiplexers at 300 mK and followers at 2 K (similar to those used for the ISOCAM arrays) will be developed to read out the thermometer bridge circuits.

It is planned that the development and evaluation of the three array options will continue until late 1999 when fully space qualifiable demonstration arrays must be available. At this time a decision will be made on which option to fly, based on the demonstrated performance of the arrays, their compatibility with the SPIRE design, and the ability to produce reliable high quality arrays. In the event that none of the planar array technologies is sufficiently advanced for inclusion in the instrument, a fall back option will be chosen that uses 2.0Fλ feed-horn coupled spider web bolometers read out by NTD germanium thermistors.

4 SENSITIVITY ESTIMATION

The sensitivity of SPIRE has been estimated under the assumptions listed below. We have adopted the more conservative feed-horn fed bolometer arrays, similar to those already working in SCUBA and other ground-based instruments. The instrument sensitivity is summarised in Fig. 5.

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:	Three arrays of hexagonally close-packed 2.0Fλ pixels		
	Central wavelengths	250 350 and 500 µm	
	Numbers of pixels	61 37 and 19 (back-up option)	
	Beam FWHM	18 25 and 36 arcseconds	
	Field of view of each array	4 arcminutes	
	Overall optics efficiency	30%	
	Filter widths($\lambda/\Delta\lambda$)	3	
	Chopping efficiency factor	0.45	
	Observing efficiency	90% (point source); 80% (mapping)	
	Required jiggle step size	9 arcseconds (full spatial sampling at 250 µm)	
FTS spectrometer:	Three arrays of hexagonally close-packed 2.0Fλ pixels at the two FTS output ports		
	Nominal bands	33.5-50 cm^{-1} (200-300 µm)	15-33.5 cm^{-1} (300-670 µm)
	Numbers of pixels	37	19 (back-up option)
	Field of view	2 arcminutes	
	Max. spectral resolution	0.04 cm^{-1} ($\lambda/\Delta\lambda$ = 1000 at 250 µm)	
	Overall optics efficiency	12% (including polarisers)	
	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. In the case of filled absorber arrays, for which the pixel size is smaller, the background power is lower by a factor of approximately 4 and the background-limited NEP is thus lower by a factor of 2. A detector NEP ~ 3 x 10^{-17} W $Hz^{-1/2}$ is therefore needed to provide background limited sensitivity

		Photometer band			**FTS band**	
		250 µm	350 µm	500 µm	200–300 µm	300–670 µm
Background power/pixel	pW	7.4	5.3	4.8	7.3	10.6
Background-limited NEP	W $Hz^{-1/2}$ x 10^{-17}	12.3	8.7	7.0	12.3	11.3

Table 1: Background power and photon noise-limited NEPs for SPIRE (feed-horn option).

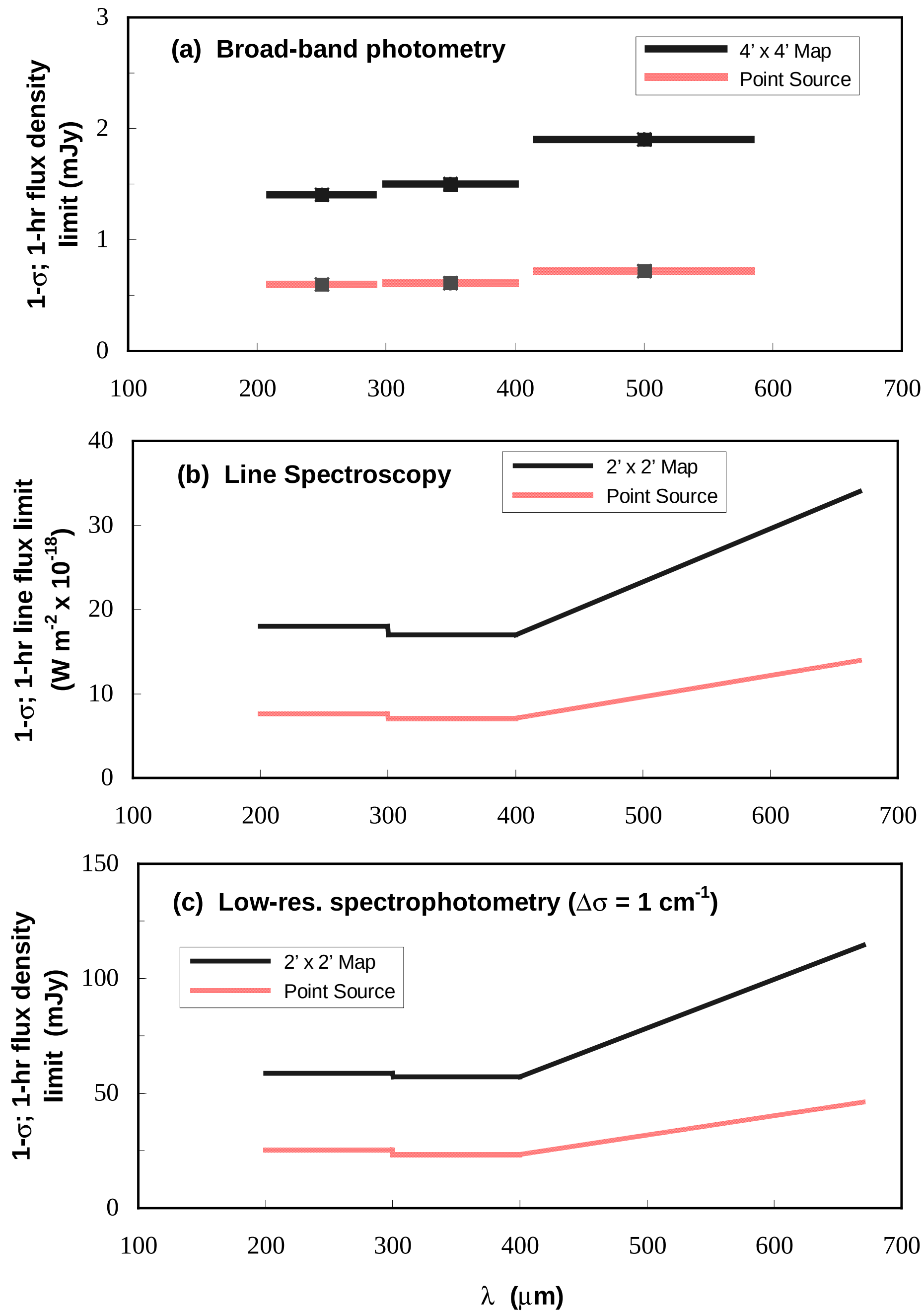

Figure 5: Estimated sensitivity of SPIRE for broad-band photometry, line spectroscopy and low-resolution spectrophotometry (spectral resolution of 1 cm^{-1}).

5 TECHNICAL CHALLENGES

Building SPIRE will require considerable technical ingenuity. Three areas have been identified in which the development of the instrument will present technical challenges:

(i) thermal-mechanical engineering: the support of significant masses at low temperatures with stringent alignment tolerances and vibration specifications, but conforming to the very strict thermal budgets allocated to the FIRST focal plane instruments;

(ii) stray light control: the elimination of spurious thermal background radiation from the instrument enclosure, as this could degrade the sensitivity of the detectors or lead to systematic errors in the instrument calibration;

(iii) the development and proof of planar detector arrays in time for flight, and the solution to the problem of the heavy on-board data processing which they will require.

6 THE SPIRE CONSORTIUM

SPIRE has been proposed in response to ESA's Announcement of Opportunity by a consortium of European and US 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; Royal Observatory Edinburgh, UK; Rutherford Appleton Laboratory, Oxfordshire, UK; Stockholm Observatory, Sweden; Università di Padova, Italy;

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