4 INSTRUMENT DESCRIPTION

4.1 INTRODUCTION

For low background direct detection at wavelengths longer than around 200 μm, the most sensitive detectors are cryogenic bolometers operating at temperatures in the 0.1 - 0.3 K range.

SPIRE (Spectral & Photometric Imaging REceiver) is a bolometer instrument comprising a three-band imaging photometer covering the 200-500 μm range and an imaging Fourier Transform Spectrometer (FTS) with a spectral resolution of at least 0.4 cm^{-1} (corresponding to $\lambda/\Delta\lambda = 100$ at 250 μm, covering wavelengths between 200 and 670 μm. The detectors are bolometer arrays cooled to 300 mK using a ^{3}He refrigerator. The photometer is optimised for deep photometric surveys, and can observe simultaneously the same field of view of 4 x 8 arcminutes in all three bands.

4.2 SCIENTIFIC RATIONALE

The wavelength range 200 - 700 μm is largely unexplored. The thermal emission from many astrophysical sources peaks in this part of the spectrum, including comets, planets, star-forming molecular cloud cores, and starburst galaxies. The short submillimetre region is also rich in atomic and molecular transitions which can be used to probe the chemistry and physical conditions in these sources.

Wavelengths between 200 and 350 μm are not observable from the ground and have not be observed by ISO. Between 350 μm and 700 μm, some low transparency submillimetre windows allow some observations to be made with difficulty from the ground, but with far lower sensitivity than can be achieved from space.

One of the most important scientific projects for the HERSCHEL mission is to investigate the statistics and physics of galaxy formation at high redshift. This requires the ability to carry out deep photometric imaging at far-infrared and submillimetre wavelengths to discover objects, and the ability to follow up the survey observations with spectroscopy of selected sources. The HERSCHEL SPIRE instrument is essential for this programme, and is being designed so as to be optimised for these extragalactic imaging and spectral surveys. Another key scientific project for SPIRE is a sensitive unbiased search for proto-stellar objects within our own galaxy. This will also be followed up by spectral observations using SPIRE, other HERSCHEL instruments and ground-based facilities.

4.3 INSTRUMENT OVERVIEW

SPIRE contains a three-band imaging photometer and an imaging Fourier Transform Spectrometer (FTS), both of which use 0.3-K “spider-web” NTD germanium bolometers cooled by a ^{3}He refrigerator. The bolometers are coupled to the telescope by close-packed single-mode conical feedhorns. 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 photometer arrays provide broad-band photometry ($\lambda/\Delta\lambda \approx 3$) in wavelength bands centred on 250, 350 and 500 µm. The 250, 350 and 500 µm arrays have 139, 88, and 43 detectors respectively, making a total of 280. 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 which serves to null the thermal background from the telescope and to provide absolute calibration. 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 has three separate temperature stages at nominal temperatures of 4 K, 2 K (provided by the HERSCHEL 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 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. Two JFET preamplifier modules (one for the photometer and one for the FTS) are attached to the optical bench close to the 4-K enclosure, with the JFETs heated internally to their optimum operating temperature of ~ 120 K.

The SPIRE warm electronics consist of two boxes with direct connection to the FPU, the Detector Control Unit (DCU) and the Focal Plane Control Unit (FCU) (together these boxes are termed the Detector Readout and Control Unit (DRCU)) plus a Digital Processing Unit (DPU) with interfaces to the other two boxes and the spacecraft data handling system. The DCU provides bias and signal conditioning for the detector arrays and cold readout electronics and reads out the detector signals. The FCU controls the FPU mechanisms and the ^{3}He cooler and handles housekeeping measurements. The DPU acts as the interface to the spacecraft, including instrument commanding and formats science and housekeeping data for telemetry to the ground.

4.4 HARDWARE DESCRIPTION

The SPIRE instrument consists of:

HSFPU	Cold Focal Plane Unit (FPU): This interfaces to the cryostat optical bench, and the 4-K and 2-K temperature stages provided by the cryostat. Within the unit, further cooling of the detector arrays to a temperature of around 300 mK is provided by a ^{3}He refrigerator which is part of the instrument.
HSFBP	JFET box for the photometer detectors This box is mounted on the optical bench next to the photometer side of FPU, and contains JFET preamplifiers for the detector signals. The JFETs operate at around 120 K, and are thermally isolated inside the enclosure.
HSFBS	JFET box for the spectrometer detectors This box is mounted on the optical bench next to the spectrometer side of the FPU, and contains JFET preamplifiers for the detector signals. The JFETs operate at around 120 K, and are thermally isolated inside the enclosure.
HSDCU	Detector Readout Unit (on HERSCHEL SVM) A warm analogue electronics box for detector read-out analogue signal processing, multiplexing, A/D conversion, and array sequencing.
HSFCU	Focal Plane Control Unit (on HERSCHEL SVM) A warm analogue electronics box for mechanism control, temperature sensing and general housekeeping and ^{3}He refrigerator operation.
HSDPU	Digital Processing Unit (on HERSCHEL SVM) A warm digital electronics box for signal processing and instrument commanding and interfacing to the spacecraft telemetry.
HSWIH	Warm interconnect harnesses (on HERSCHEL SVM) Harnesses making connections between the SPIRE warm electronics boxes.

4.5 SOFTWARE DESCRIPTION

The OBS will carry out the following functions:

- Read and log housekeeping data
- Control and monitor the instrument mechanisms and internal calibration sources
- Carry out pre-defined observing sequences
- Implement pre-defined procedures on detection of instrument anomalies

The on-board software (OBS) will be written in “C” (TBC) language and will be designed to allow the instrument to operate in an autonomous fashion for 48 hours as required in the IID-A. The basic implication of this requirement is that there must be the facility to store enough commands for a 48 observing programme and enough mass memory on the satellite to store 48 hours of instrument telemetry. More sophisticated autonomy functions may include the on-board analysis of scientific or housekeeping data and the ability to react on the basis of that analysis. The type of automatic operation undertaken following such an analysis may range from the raising of a warning flag to the switching over to a redundant sub-system or the switching off of a defective sub-system. All autonomy functions will require extensive evaluation and test before they are implemented to avoid the possibility of instrument failure. No instrument autonomy mode will be implemented that will affect the satellite operation.

Memory load commands will be used to send single instructions to the instrument or to command pre-defined sequences of operations. The command words will be interpreted by the OBS according to a given algorithm and the relevant sequence of digital commands sent to the subsystems. Each command will be formed with a variable number of words having the following general structure: (i) a header describing the command function; (ii) the number of words to follow; (iii) the new values of the parameters, if any. There will be at least four types of commands: macro commands, subsystem commands, peek-and-poke commands; and spare commands. The macro commands define the timing and sequence of instrument operation. The subsystem commands allow the immediate control of each instrument subsystem. The peek-and-poke commands allow the down-link of RAM or ROM content as well as the ability up-link patches, new programmes or tables. There will also be the possibility to run new commands by up-linking the specific code in RAM recalled by the spare command.

A detailed description of the on-board software will be given in Chapter 5

4.6 OPERATING MODES

This section gives a brief description of the operating modes for the SPIRE instrument.

4.6.1 OFF Mode

All instrument sub-systems will be switched off - including the DPU and there will be no instrument telemetry.

4.6.2 Initialise (INIT) Mode

This is an intermediate mode between OFF and ON. This will be the mode the instrument enters after a power on or re-boot. In this mode only a limited sub-set of commands may be executed. This mode allows updates of DPU on-board software and/or tables to be carried out safely before they are used for instrument control.

4.6.3 ON Mode

The DPU will be switched on and can receive and interpret all instrument commands, but no other sub-systems will be switched on (including the DRCU). For engineering purposes it will be possible to command the instrument to switch on individual sub-systems from this mode. Full DPU housekeeping data will be telemetered.

4.6.4 Ready (REDY) Mode

The DPU and DRCU are powered on and the on-board software is ready to receive commands. No other sub-systems are switched on in this mode. DRCU housekeeping data will be telemetered.

4.6.5 Standby (STBY) Mode

The spacecraft may be pointed in an arbitrary direction (observing with another instrument for instance). The instrument will telemeter only housekeeping information, and perhaps some degraded science data -see below, at a rate very much lower than the full telemetry bandwidth. This is presently baselined to be the photometer detectors on and at 300 mK i.e. the cooler will have been recycled previous to entering STANDBY. All other sub-systems will be switched off.

4.6.6 Observe Mode (OBSV) Mode

There are two basic sub-modes for the observe mode Photometer and Spectrometer. The details of the OBSERVATIONS to be carried out in OBSERVE mode are given in section 4.7.

4.6.7 Cooler Recycle (CREC) Mode

The ^{3}He cooler requires recycling every 46 hours (TBC). During this time the instrument will be switched off except for vital housekeeping and cooler functions (TBC).

4.6.8 SAFE Mode

The instrument will be switched to SAFE mode in the event of any anomalous situation occurring whilst in autonomous operation. This will be with the DPU on having been rebooted from a restricted set of software stored in ROM.

4.7 OBSERVING MODES

The spacecraft will be pointed in a specific direction or, for mapping, will either slew slowly over a given region of the sky, or execute a raster pattern by movements of the telescope. The instrument will take scientifically meaningful data and use the full telemetry bandwidth. It is assumed that any calibrations required will also be done in the observe mode (TBC).

4.7.1 Photometer Observing Modes

The photometer can carry out essentially three kinds of observation: chopping, jiggling, and scanning, and it is envisaged that these will form the basis of three Astronomical Observation Templates (AOTs) to allow astronomers to specify their observations. The three kinds of observation are implemented as 6 (TBC) observing modes, named POFs (Photometer Observatory Functions), which are briefly described below. Provision is also made for additional POFs for peak-up and special engineering modes.

4.7.1.1 Observation: Point source photometry

POF1 Chop without jiggling:
This mode is for point source observations with reliable telescope pointing. The SPIRE Beam Steering Mechanism is used to chop between two positions on the sky

at a frequency of typically 2 Hz. The telescope may optionally be nodded with a nod period of typically three minutes.

POF2 Seven-point jiggle map:
This mode is for point source observations for which the telescope pointing or the source co-ordinates are not deemed sufficiently accurate. The SPIRE BSM chops and also executes a seven-point map around the nominal position. Nodding is optional.

4.7.1.2 Observation: Jiggle map

POF3 n-point jiggle map:
This mode is designed for mapping of extended sources. It is similar to POF2 except that the nominal value of n is 64 rather than 7. It produces a fully sampled map of a 4 x 4 arcminute area.

POF4 Raster map:
This is the same as POF3 except that maps of large regions can be built up by using the telescope rastering capability.

4.7.1.3 Observation: Scan map

POF5 Scan map without chopping:
This mode is used for mapping areas much larger than the SPIRE field of view. The SPIRE BSM is inactive, and the spacecraft is scanned continuously across the sky to modulate the detector signals.

POF6 Scan map with chopping:
This mode is the same as POF5 except that the SPIRE BSM implements chopping. It allows for the possibility of excess 1/f noise by permitting signal modulation at frequencies higher that POF5.

4.7.1.4 Others

POF7 Photometer peak-up (TBD):
This mode allows the necessary pointing offsets to be determined in order to allow implementation of POF1 rather than POF2. The observation itself is exactly the same as POF3. On completion, the SPIRE DPU computes the offsets between the telescope pointed position and the source peak emission, and sends this information to the spacecraft, which can then implement the necessary pointing corrections.

POF8 Operate photometer calibrator:
The SPIRE photometer internal calibrator is energised with a pre-determined sequence and the corresponding detector signals are recorded.

POF9 Special engineering/commissioning modes (TBD).

4.7.2 Spectrometer Observing Modes

Any astronomical observations with the spectrometer can be implemented with only one mode. We therefore envisage only one AOT being defined to assist astronomers in preparing the input necessary to specify the observation.

Two Spectrometer Observatory Functions (SOFs) are defined for low/medium resolution and high resolution to take account of any differences in the on-board processing that might be required.

SOF1: Point source spectrum
SOF2: Fully sampled spectral map

In all cases, the telescope pointing and/or Beam Steering Mirror position are kept fixed while the FTS mirror is scanned a predetermined number of times to generate interferograms from which the source spectrum can be derived.

4.7.3 Other Modes

4.7.3.1 Photometer Serendipity

During spacecraft slews scientifically useful information can be obtained without the necessity of using the focal plane chopper - essentially these are rapid scan maps. The chopper and spectrometer mechanisms will be switched off in this mode. Accurate pointing information will be required from the AOCS to reconstruct the slew path in the data analysis on the ground.

4.7.3.2 Photometer Parallel

When observations are being made with PACS, scientifically useful data may be obtainable from the photometer, albeit with degraded sensitivity and spatial resolution. In this mode a science data packet will be telemetered alongside the standard housekeeping data. The chopper and spectrometer mechanisms will be switched off in this mode. The feasibility and scientific desirability of this mode is TBD.

4.7.4 Real-Time Commanding

During ground contact it may be necessary to command the instrument in real time and analyse the resultant data on the ground in near real time for instrument testing and debugging purposes. In this case the full telemetry bandwidth will be required for the duration of the instrument test in question. It is not anticipated that this will occur frequently.

4.7.5 Commissioning/calibration Mode

During the commissioning and performance verification phases of mission operations, many housekeeping and other health check parameters will be unknown or poorly defined. This mode allows the limits on selected health check parameters to be ignored by whatever real time monitoring systems are in place on the spacecraft/instrument.

4.7.6 FPU operations at Ambient Temperature

TBD. It is anticipated that functional checks will be possible for mechanisms and housekeeping lines. The detectors will not function at ambient temperature. Limited verification of the readout electronics may be possible.

4.7.7 FPU Orientation

During ground tests the FTS mechanism can only operate when the FPU is on its side. In addition, there is a restriction on the orientation of the ^{3}He cooler during recycling.

4.8 INSTRUMENT REQUIREMENTS AND PERFORMANCE SPECIFICATION

4.8.1 Scientific Requirements

The scientific performance requirements for SPIRE are summarised in the *SPIRE Scientific Requirements Document* as follows:

Requirement SRD-R 1: The photometer should be capable of diffraction-limited extragalactic blind surveys of at least 60 sq. deg. of the sky, to 1-σ detection limit of 3 mJy in all bands with an observing time of six months or less.

Requirement SRD-R 2: The photometer should be capable of a galactic survey covering 1 deg. sq. to a 1-σ depth of 3 mJy at 250 μm within an observing time of one month or less.

Requirement SRD-R 3: Maximising the ‘mapping speed’ at which confusion limit is reached over a large area of sky is the primary science driver. This means maximising sensitivity and field-of-view (FOV) but NOT at the expense of spatial resolution.

Requirement SRD-R 4: The photometer observing modes should provide a mechanism for telemetering undifferenced samples to the ground.

Requirement SRD-R 5: The photometer should have an observing mode that permits accurate measurement of the point spread function.

Requirement SRD-R 6: Optical field distortion should be less than 10% across the photometer field of view.

Requirement SRD-R 7: The photometer field of view shall be at least 4 x 4 arcminutes, with a goal of 4 x 8 arcminutes.

Requirement SRD-R 8: For 2Fλ feedhorns, crosstalk shall be less than 1% (goal 0.5%) for adjacent detectors and 0.1% or less (goal 0.05%) for all non-adjacent detectors in the same array; for 0.5Fλ pixels, the requirement is 5% (goal 2%) to adjacent detectors and 0.1% (goal 0.05%) to all others. (Note: This requirement is under review).

Requirement SRD-R 9: The maximum available chop throw shall be at least 4 arcminutes; the minimum shall 10 arcseconds or less.

Requirement SRD-R 10: The rms detector NEP variation across any photometer array should be less than 20%.

Requirement SRD-R 11: The photometer dynamic range for astronomical signals shall be 12 bits or higher.

Requirement SRD-R 12: SPIRE absolute photometric accuracy shall be 15% or better at all wavelengths, with a goal of 10%.

Requirement SRD-R 13: The relative photometric accuracy should be 10% or better with a goal or 5%.

Requirement SRD-R 14: SPIRE photometric measurements shall be linear to 5% over a dynamic range of 4000 for astronomical signals.

Requirement SRD-R 15: For feedhorn detectors, the overlapping sets of three detectors at the three wavelengths should be co-aligned to within 2.0 arcsecond on the sky (goal = 1 arcsecond).

Requirement SRD-R 16: The spectrometer design shall be optimised for optimum sensitivity to point sources but shall have an imaging capability with the largest possible field of view that can be accommodated.

Requirement SRD-R 17: The sensitivity of the FTS at any spectral resolution up to the goal value shall be limited by the photon noise from the FIRST telescope within the chosen passband.

Requirement SRD-R 18: The spectrometer dynamic range for astronomical signals shall be 12 bits or higher.

Requirement SRD-R 19: The FTS absolute photometric accuracy at the required spectral resolution shall be 15% or better at all wavelengths, with a goal of 10%.

Requirement SRD-R 20: The FTS shall be capable of making spectrophotometric measurements with a resolution of 2 cm^{-1}, with a goal of 4 cm^{-1}.

Requirement SRD-R 21: The width of the FTS instrument response function at the required spectral resolution shall be uniform to within 10% across the field of view.

Requirement SRD-R 22: The maximum spectral resolution of the FTS shall be at least 0.4 cm^{-1} with a goal of 0.04 cm^{-1}.

Requirement SRD-R 23: The SPIRE photometer shall have an observing mode capable of implementing a 64-point jiggle map to produce a fully sampled image of a 4 x 4 arcminute region.

Requirement SRD-R 24: The photometer observing modes shall include provision for 5-point or 7-point jiggle maps for accurate point source photometry.

Requirement SRD-R 25: The photometer shall have a "peak-up" observing mode capable of being implemented using the beam steering mirror.

4.8.2 Instrument Performance Estimates

4.8.2.1 Assumptions

The sensitivity of SPIRE has been estimated under the assumptions listed in Table 4.1.

Table 4.1: Assumptions for SPIRE Performance Estimation

Telescope temperature (K)	80		
Telescope emissivity	0.04		
Telescope used diameter (m) (1)	3.29		
No. of observable hours per 24-hr period	21		
Photometer			
Bands (μm)	250	350	500
Numbers of detectors	139	88	43
Beam FWHM (arcsec.)	17	24	35
Bolometer DQE (2)	0.6	0.7	0.7
Throughput	λ^2		
Bolometer yield	0.8		
Feed-horn/cavity efficiency (3)	0.7		
Field of view (arcmin.) Scan mapping	4 x 8		
Field mapping	4 x 4		
Overall instrument transmission	0.3		
Filter widths ($\lambda/\Delta\lambda$)	3.3		
Observing efficiency (slewing, setting up, etc.)	0.9		
Chopping efficiency factor	0.45		
Reduction in telescope background by cold stop (4)	0.8		
FTS spectrometer			
Bands (μm)	200-300	300-670	
Numbers of detectors	37	19	
Bolometer DQE	0.6	0.7	
Feed-horn/cavity efficiency	0.70		
Field of view diameter (arcmin.)	2.6		
Max. spectral resolution (cm^{-1})	0.04		
Overall instrument transmission	0.15		
Signal modulation efficiency	0.5		
Observing efficiency	0.8		
Electrical filter efficiency	0.8		

Notes:

1. The telescope secondary mirror is the pupil stop for the system, so that the outer edges of the primary mirror are not seen by the detectors. This is important to make sure that radiation from highly emissive elements beyond the primary reflector does not contribute stray light.
2. The bolometer DQE (Detective Quantum Efficiency) is defined as $\left[\frac{NEP_{ph}}{NEP_{Total}}\right]^2$ where NEP_{ph} is the photon noise NEP due to the absorbed radiant power and NEP_{Total} is the overall NEP including the contribution from the bolometer noise.
3. This is the overall absorption efficiency of the combination of feed-horn, cavity and bolometer element.
4. A fraction of the feedhorn throughput falls outside the solid angle defined by the photometer 2-K cold stop and is thus terminated on a cold (non-emitting) surface rather than on the 4% emissive 80-K telescope. This reduces the background power on the detector.

The background power levels on the SPIRE detectors dominated by the telescope emission), and the corresponding photon noise limited NEP values are given in Table 4.2.

Table 4.2: Background Power and Photon Noise Levels

		Photometer			**FTS band (mm)**	
		250	350	500	200-300	300-670
Background	pW	3.9	3.2	2.0	6.0	11
Background-limited NEP	W $Hz^{-1/2}$ x 10^{-17}	8.1	6.1	4.5	10	11
Total NEP (inc. detector)	W $Hz^{-1/2}$ x 10^{-17}	10	7.3	5.4	12	14

The estimated sensitivity levels for SPIRE are summarised in Table 4.3. The figures quoted are the nominal values, with an overall uncertaintyof of around 50% to take into account uncertainties in instrument parameters, particularly feedhorn efficiency, detector DQE, and overall transmission efficiency. The pixel size will be increasingly mis-matched to the diffraction spot size. The trade-off between wavelength coverage and sensitivity of the long-wavelength FTS band must be studied in detail. At the moment, we estimate an effective loss of efficiency of a factor of two at 670 μm, and scale linearly for wavelengths between 400 and 670 μm. Performance beyond 400 μm may have to be compromised to maintain the desired sensitivity below 400 μm.

Table 4.3: SPIRE Estimated Sensitivity

Photometry					
λ	µm		250	350	500
ΔS(5-σ; 1-hr)	mJy	Point source (7-point)	2.5	2.6	2.9
		4’ x 4’ jiggle map	8.8	8.7	9.1
		4’ x 8’ scan map	7.3	7.2	7.5
Time (days) to map 1 deg.^{2} to 3 mJy		1^o x 1^o scan map	1.8	1.7	1.9

Line spectroscopy Ds = **0.04 cm^{-1}**					
λ	µm		200	400	670
ΔS (5-σ; 1-hr)	W m^{-2} x 10^{-17}	Point source	3.4	3.9	7.8
		2.6’ map	9.0	10	21

Low-resolution spectrophotometry Ds = **1 cm^{-1}**					
λ	µm		200	400	670
ΔS (5-σ; 1-hr)	mJy	Point source	110	130	260
		2.6’ map	300	350	700

Note: For the FTS, limiting flux density is inversely proportional to spectral resolution (Δσ). Limiting line flux is independent of spectral resolution (for an unresolved line).

These estimated sensitivity levels are comparable to the figures in the SPIRE proposal.