4 Instrument calibration

4.1 Calibration requirements

The calibration requirements for SPIRE for both ground and in-orbit testing will be laid out in the *SPIRE Calibration Requirements Document* which will be submitted to ESA for approval. This document will be updated in line with the FIRST calibration requirements, as and when they are established. We give here an outline of the major calibration issues to be addressed in the instrument ground and in-orbit calibration. The calibration specifications on these, and any others that arise during the instrument development, will be finalised as part of the instrument Critical Design Review.

4.1.1 Photometric accuracy

The primary scientific aim of SPIRE is to provide high accuracy imaging photometry and spectrophotometry. To this end it is of crucial importance that, as well as establishing the absolute photometric accuracy of the instrument to an on-axis source, any variation in photometric performance across the imaging arrays is accurately characterised on the ground and monitored in flight. The spectrometer channel on the instrument is primarily designed to do medium resolution spectroscopy of point like objects. It is important to the understanding of the physical conditions in the objects under study to give a highly accurate ratio between the fluxes in various spectral lines or parts of the continuum emission, as well as to associate an absolute flux to any one line or spectral band. The photometric performance of the instrument may also change with time owing to changes in the temperature environment of the instrument or the telescope, gain drifts in the read out electronics etc. Any drift in the photometric performance as a function of time - whatever the cause - will be characterised and a suitable scheme for monitoring it in flight devised and implemented.

It is not possible at this early stage of the instrument development to set hard limits on the requirements for the ground test programme or the in-flight calibration scheme that are to fulfil the general requirements set out above. However, the following requirements can be identified as a minimum.

1. The ground-based and in-flight calibration will establish the absolute photometric calibration of SPIRE observations to an accuracy of 10% or better. The photometric calibration will be confirmed in orbit by the use of known astronomical sources.

2. The absolute responsivity and noise of each pixel in the arrays shall be measured to an accuracy of a few percent.

3. The ground-based calibration of the instrument will establish the pixel-to-pixel variation in the performance of each array, (to within a small percentage of the mean value of the array as a whole) under operating conditions as close as possible to those expected in-orbit.

4. The in-orbit calibration scheme will be capable of establishing the pixel-to-pixel variation to within the same limits.

5. The ground-based calibration will characterise any variation in the performance of the arrays (e.g., responsivity and noise) as a function of detector and environmental parameters such as the bias and operating temperature of the arrays, and the temperatures of the shields within the instrument. This shall be done while simulating as closely as possible the conditions expected in-orbit.

6. The in-orbit calibration scheme shall be capable of similarly characterising any variations in performance with the same parameters.

7. The instrument spectral pass-bands will be accurately measured on the ground before integration with the FIRST telescope with the use of a telescope simulator with spectrally discrete sources

and/or a laboratory FTS. This will be confirmed in orbit by the use of known astronomical sources.

4.1.2 FTS-specific calibration

In addition to the purely photometric issues raised above, the FTS calibration will have to address the following:

(i) wavelength calibration;
(ii) mirror mechanism position measurement and repeatability.;
(iii) accuracy requirements on the mechanism sampling step and total travel;
(iv) tilt and de-centre of the moving mirrors;
(v) velocity stability of the moving mirrors;
(vi) velocity measurement accuracy and sampling correction schemes;
(vii) relative alignment of the polarisers.

Most of the problems that can arise with the operation of an FTS will lead to errors in the interferograms that in turn lead to errors in the derived spectrum or loss of spectral resolution. Accurate ground calibration of the drive mechanism and mirror position measurement before integration in the instrument is essential to characterise fully the instrument behaviour. Ground calibration of the integrated instrument will be designed to confirm the performance of the mirror mechanism and the instrument alignment.

After the instrument has been integrated with the FIRST telescope, it will not be possible to verify the spectroscopic performance; no spectral calibration source will be installed. Therefore, the spectral performance of the instrument will be verified in orbit by the use of astronomical sources with lines of known wavelengths and intrinsic widths.

4.1.3 Bolometer-specific calibration

The SPIRE bolometer arrays will be fully tested and characterised before integration into the instrument. Their performance will be verified during ground calibration and in flight. The main parameters to be determined are:

(i) optimum operating temperature and bias ranges;
(ii) responsivity and noise spectra;
(iii) speed of response;
(iv) linearity;
(v) cross-talk between pixels;
(vi) response to ionising radiation;
(vii) response to microphonic disturbance.
(viii) amplifier gain and noise performance;
(ix) angular response.

4.1.4 Other considerations

Other aspects of the instrument performance as a complete system will also characterised during ground and in-orbit calibration. These include:

(i) response to off axis point sources;
(ii) response to extended sources;
(iii) field of view of the arrays;
(iv) beam profile as a function of position within the field of view;
(v) stray-light as a function of mechanism position and pixel location;
(vi) image distortion and aberrations;
(vii) cooler hold time and temperature stability;
(viii) instrument response to temperature fluctuations.

Again, it is not possible to set limits on the accuracy to which these should be calibrated at this early stage in the instrument development.

4.1.5 On-board calibration sources

The on-board calibration sources will be capable of fulfilling the calibration requirements outlined here and to be detailed in the calibration requirements document. They are described in outline in section 2. These sources will be calibrated against black bodies during ground calibration and their calibration confirmed by the use of known astronomical sources once in-orbit.

4.1.6 Astronomical sources

Although the on-board calibrators may be capable of providing some indication of the absolute flux levels, they are required only to allow relative changes in system performance to be monitored. Furthermore, the instrument absolute photometric calibration will not have been verified on the ground after integration with the FIRST telescope and satellite. A catalogue of astronomical sources with known spectral characteristics will therefore need to be established to provide the absolute calibration of the instrument in-orbit. This will be based on a combination of ground-based data from facilities such as the JCMT (longer wavelengths), and ISO (shorter wavelengths).

4.2 Ground calibration facility

4.2.1 Options for the calibration facility

The main ground calibration facility for SPIRE will need to replicate the thermal and optical environment present on the FIRST satellite. Two options for the calibration facility are being considered:

(i) an 80-K telescope simulator feeding a separate instrument cryostat with simulated thermal and mechanical interfaces;

(ii) a warm telescope simulator feeding a separate instrument cryostat with simulated thermal and mechanical interfaces.

Option (i) consists of a large nitrogen cryostat housing a telescope simulator similar in concept to the one used for the ISO LWS, UKIRT or JCMT. At the input of the telescope simulator would be a plate cooled to 4 K or below for the calibration sources and filters. The instrument would be housed in a separate cryostat with the appropriate thermal interfaces - see below. This option has the advantage that there need be little additional filtering between the source and the instrument, therefore the sources used can accurately reflect the temperature of the sources that will actually be observed in-orbit.

The second option would employ an instrument cryostat in the same way as the first, but with filtering on each thermal shield used to reduce the radiation from the 300-K room and a warm telescope simulator mounted on a optical bench. As the instrument will be working in the Rayleigh-Jeans region of the spectrum, the filtering can be adjusted to give the correct level of background power on the detector arrays whilst allowing hot black body radiation (~ 800 K) or radiation from multiplier sources or a far infrared laser to be used for calibration purposes. The spectral shape of a cooler black body (20-40 K) can be replicated by the use of suitable filters in front of the hot black body. This option would be much simpler to implement and operate than the first one.

A study on which option is appropriate for the calibration of SPIRE will be conducted with the aim of having a working facility in time for the EQM test and calibration. Whichever option is chosen, the sources to be used will simulate on-axis point sources, uniformly extended sources and off-axis point

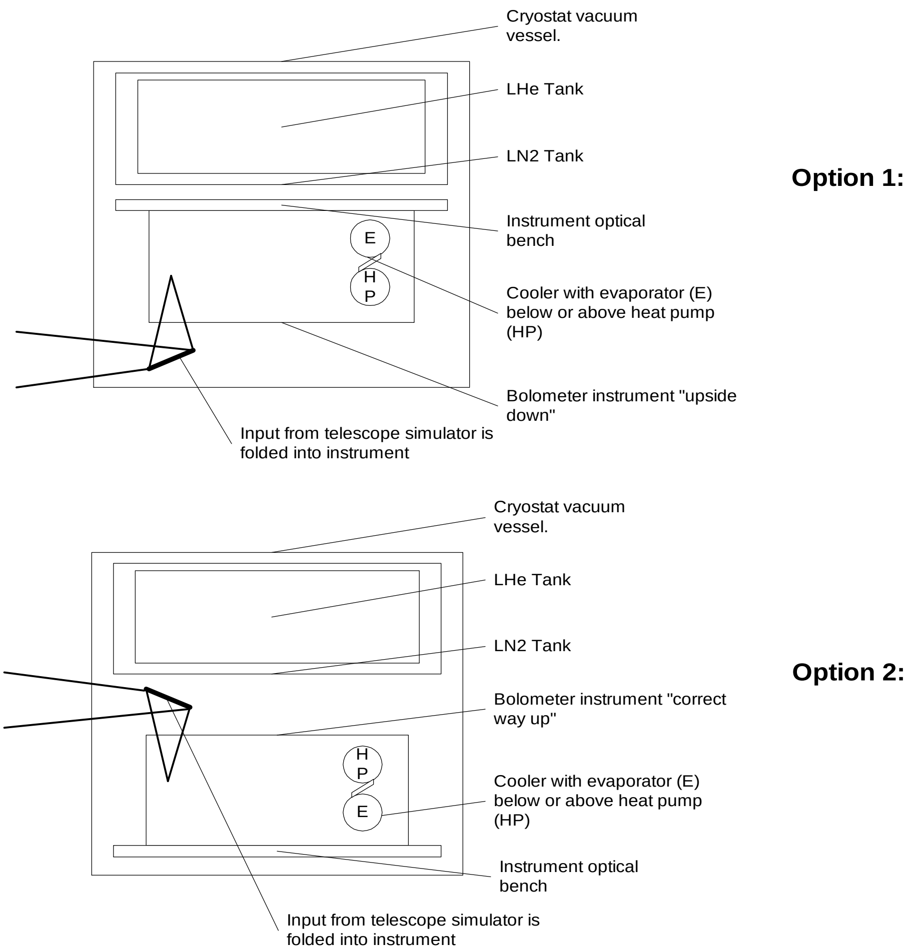

Figure 4.1: The options for the orientation of the instrument in the test facility cryostat.

sources. Both broad band and narrow band sources will be employed (see below for a more detailed discussion of the source types envisaged).

4.2.2 Instrument test cryostat

The instrument test cryostat itself will provide the same temperature interfaces as present on the FIRST cryostat, and also simulate as accurately as possible the thermal and mechanical environment of the FIRST cryostat. Some beam folding is likely to be necessary in order to simplify the mounting of the instrument within the test cryostat. Careful consideration must be given to the instrument mounting in order to trade off the complexity of the test cryostat against the need to provide a realistic mechanical environment and to ensure the correct orientation of the ^{3}He sorption cooler for ground testing. In option 1 the instrument will be in a different orientation compared to when it is integrated with the FIRST satellite - thus making comparisons between instrument level and system level test more difficult. Option 2 has the instrument in the same orientation as in the FIRST satellite, but the cryostat may be more complicated to build. Option 2 will be studied carefully - if the cryostat can be built like this without major additional expense and operational complexity it will be the favoured option as it will make comparison of mechanism performance between the instrument and satellite level tests very much more meaningful.

4.2.3 Calibration sources

A number of types of calibration source will be required to fully test the operation and performance of SPIRE.

Broad band point-like sources: These could be "real" cryogenic black bodies with integrating cavities feeding the telescope simulator via feed horns or Winston cones to ensure a well controlled beam shape through the system. Alternatively thermal illuminator type sources could be used, again via feed horns or Winston cones or simply through light-pipe type feeds. The advantage of using black bodies is that they can provide an absolute calibration of the system. Thermal illuminators are smaller and could be used to simulate a variety of positions in the field of view without the necessity for moving mirrors etc. In practice a mixture of the two may be necessary: the black body for the absolute calibration of the on-axis position and thermal illuminators for the relative calibration as a function of field position. A steerable mirror could also be implemented to simulate off-axis point sources.

Broad-band extended sources: A check of the response of the instrument to a broad-band source that over-fills the field of view will be required. This could be done by using a point like source and moving its image around in the field with a steerable mirror or by using a number of point sources placed at a variety of positions in the field and individually controllable (see above). Moving the image of a single source around the field of view is both slow and prone to problems with changes in the stray-light environment when optical elements are moved. Whilst the option of having individually controllable point sources is attractive, in practice the number of such sources will be limited. Therefore, to provide the final test of the instrument response to truly extended sources, a calibration source of controlled temperature that fills the field of view will be necessary.

Monochromatic multiplier sources: Tunable spectral sources will be required to verify the operation and wavelength calibration of the FTS and to measure the instrument response function. In addition, this type of source will be used to map the filter response of the photometric channel of the instrument and to ensure that no channel fringing is present in the instrument optics. The type of source identified for this application employs a multiplier fed by a co-axial cable from a laboratory frequency synthesiser. This has the advantage that the frequency generated can be externally controlled via a computer interface to the instrument EGSE. This type of multiplier has been tested up to frequencies of 1 THz with output powers in the nW range - sufficient for the purposes of SPIRE. Two device types may be required: one operating from 500 GHz to 1 THz and another from 1 - 1.8 THz. Some development work will be necessary to ensure the correct design of the latter device. These devices produce a frequency "comb" with harmonics separated by the base frequency of the synthesiser. Therefore, a Fabry-Perot tracking filter may be necessary to isolate the frequency of interest.

Monochromatic submillimetre laser source: Although, given the relatively low resolving power of the SPIRE FTS, a submillimetre laser is not strictly required, one could be useful for testing the response of the instrument to sources of radiation very far off axis. The advantage of the laser is that it provides a high-power collimated source of radiation (up to 100 mW). It could be used, therefore, with the instrument cryostat detached from the telescope simulator to test the instrument response to radiation from far outside the field of view.

External FTS: The spectral response function of the photometer instrument within the three pass-bands can be measured across by applying a broad-band signal to the instrument through an external Fourier transform spectrometer. This may be done in addition to measurements with tunable monochromatic sources.