SPIRE

SUBJECT: **Calibration Requirements Document**

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DOCUMENT No: **SPIRE-RAL-PRJ-001064**

ISSUE: **DRAFT for Comment** Date: **3 January 2002**

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Change Record

ISSUE	DATE	
Draft for comment	3 January 2002	First reasonable version sent out for comment to interested parties

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Glossary

ADC	Analogue to Digital Converter
AIV	Assembly, Integration and Verification
AME	Absolute Measurement Error
AME	Absolute Measurement Error
AOCS	Attitude and Orbit Control System
APART	
APE	Absolute Pointing Error
ASAP	Advanced Systems Analysis Program
AVM	Avionics Model
BDA	Bolometer Detector Array
BFL	Back Focal Length
BRO	Breault Research Organization
BSM	Beam Steering Mirror
CDMS	Command and Data Management System
CDMU	Command and Data Management Unit
CDR	Critical Design Review
CMOS	Complimentary Metal Oxide Silicon
CPU	Central Processing Unit
CVV	Cryostat Vacuum Vessel
DAQ	Data Acquisition
DCU	Detector Control Unit = HSDCU
DPU	Digital Processing Unit = HSDPU
DQE	Detective Quantum Efficiency
EGSE	Electronic Ground Support Equipment
EGSE	Electrical Ground Support Equipment
EMC	Electro-magnetic Compatibility
EMI	Electro-magnetic Interference
ESA	European Space Agency
FCU	FCU Control Unit = HSFCU
FIR	Far Infrared
FIRST	Far Infra-Red and Submillimetre Telescope
FOV	Field of View
F-P	Fabry-Perot
FPU	Focal Plane Unit
FTS	Fourier Transform Spectrometer
FWHM	Full Width Half maximum
GSFC	Goddard Space Flight Center
HK	House Keeping
HOB	Herschel Optical Bench
HPDU	Herschel Power Distribution Unit
HSDCU	Herschel-SPIRE Detector Control Unit
HSDPU	Herschel-SPIRE Digital Processing Unit
HSFCU	Herschel-SPIRE FPU Control Unit
HSO	Herschel Space Observatory
IF	Interface
IID-A	Instrument Interface Document - Part A

IID-B	Instrument Interface Document - Part B
IMF	Initial Mass Function
IR	Infrared
IRD	Instrument Requirements Document
IRTS	Infrared Telescope in Space
ISM	Interstellar Medium
JFET	Junction Field Effect Transistor
LCL	Latching Current Limiter
LIA	Lock-In Amplifier
LVDT	Linear Variable Differential Transformer
MAC	Multi Axis Controller
MCU	Mechanism Control Unit = HSMCU
MDM	
M-P	Martin-Puplett
NEP	Noise Equivalent Power
NTD	Neutron Transmutation Doped
OBS	On-Board Software
OMD	Observing Modes Document
OPD	Optical Path Difference
PACS	Photodetector Array Camera and Spectrometer
PCAL	Photometer Calibration source
PLW	Photometer, Long Wavelength
PMW	Photometer, Medium Wavelength
POF	Photometer Observatory Function
PROM	Programmable Read Only Memory
PSW	Photometer, Short Wavelength
PUS	Packet Utilisation Standard
SCAL	Spectrometer Calibration Source
SCUBA	Submillimetre Common User Bolometer Array
SED	Spectral Energy Distribution
SMEC	Spectrometer Mechanics
SMPS	Switch Mode Power Supply
SOF	Spectrometer Observatory Function
SPIRE	Spectral and Photometric Imaging Receiver
SRAM	Static Random Access Memory
SSSD	SubSystem Specification Document
STP	Standard Temperature and Pressure
SVM	Service Module
TBC	To Be Confirmed
TBD	To Be Determined
TC	Telecommand
URD	User Requirements Document
UV	Ultra Violet
WE	Warm Electronics

References

Applicable Documents

AD1 SPIRE Scientific Requirements SPIRE-UCF-PRJ-000064
AD2 SPIRE Instrument Qualification Requirements SPIRE-RAL-PRJ-000592

Reference Documents

RD1 SPIRE Design Description Document
RD2 “Long Wave Optics”, Derek Martin and John Bowen, *IEEE Trans*. *Microwave Theory and Techniques* **41** Oct 1993, pp1676-1690

1. SCOPE

In this document the calibration requirements for the Herschel SPIRE instrument for both ground and in-orbit testing are laid out. This document will evolve during the instrument definition and subsequent phases as the instrument operation and performance is better understood. It will also be updated in line with the Herschel calibration requirements as and when they are established.

2. DERIVATION OF THE CALIBRATION REQUIREMENTS

The primary scientific aim of the Herschel SPIRE instrument is to provide high accuracy three band photometry of point like objects for deep surveys in the 200 to 670 μm band. A secondary scientific programme is the medium resolution spectroscopy and low resolution spectrophotometery of point sources. To these ends the instrument has been designed with two channels (RD1):

- A three band photometer with three fixed pass bands and three arrays employing single mode feedhorns to couple the radiation from the Herchel telescope and SPIRE optics onto NTD Ge bolometer detectors – this is referred to as *the photometer* throughout this document.
- A two band Fourier Transform Spectrometer using the amplitude beam splitters and the same detectors technology as the photometer – this is referred to as *the spectrometer* throughout this document.

The Science Requirements Document (AD1 hereafter referred to as the SRD) sets out the top level performance and calibration requirements that the instrument must meet in order that it will fulfil the scientific programme of the Herschel mission.

In this section we take each of the scientific requirements and indicate those which require some aspect of the instrument performance to be measured or characterised in order to verify that the scientific requirement is met. The starting point for this is AD1 and these are discussed in section 2.1. However, some additional top-level requirements are needed in order to verify compliance with those in AD1 – these are described in section 2.2.

2.1 Scientific Requirements

The scientific requirements in the SRD can be broken down into two main categories: those that only drive the basic design of the instrument and those that specify the accuracy to which the instrument performance must be characterised. There is of course some blurring between the two but here we wish to distinguish those that will determine what calibration measurements need to be carried out and to what accuracy. In table 1 the scientific requirements are repeated from the SRD in short form and comment made on whether they require calibration measurements to be made.

SRD-ID	**Requirement**	**Comment**	**Instrument level calibration?**
SRD-R1	*The photometer shall be capable of a 60 sq. deg extragalactic survey to 1-s limit of 3 mJy in all bands in 6 months or less*	This defines the basic performance requirements for the instrument. All aspects of the instrument performance must be compatible with this requirement	Yes
SRD-R2	*The photometer shall be capable of a 1sq. deg galactic survey to a 1-s limit of 3mJy at 250 µm in 1 month or less*	The basic performance requirement here is easily met if SRD-R1 is satisfied with the exception perhaps of the ability to observe a crowded field of bright point and extended sources.	Yes
SRD-R3	*Maximising the "mapping speed" at which the confusion limit is reached…. Is the primary science driver.*	This is a statement about the priority of the quality of the PSF over the size of the FOV of the instrument and was used to drive the design	No
SRD-R4	*The photometer observing modes should provide a mechanism for telemetering undifferenced samples to the ground*	This is a statement about the problems of source identification from chopped observations and was used to define the instrument design.	No
SRD-R5	*The photometer shall have an observing mode the permits accurate measurement of the point spread function.*	The qualifying text associated with this requirement states that the psf shall be measured "*to very high accuracy*". This requirement is therefore associated both with the design of the instrument and the calibration of the main beam of the instrument. Some qualification of "*very high*" is required however!	Yes
SRD-R6	*Optical field distortion<10%*	This is set out as a design requirement. The requirement on the accuracy of the actual positions of the pixels is not explicitly detailed, although some limit is set by SRD-R15. We will interpret this as a requirement to map the pixel positions as a calibration measurement.	Yes
SRD-R7	*Photometer FOV at least 4x4 arcminutes*	A design driver only	No

SRD-ID	**Requirement**	**Comment**	**Instrument level calibration?**
SRD-R8	*Crosstalk <1% (0.5% goal) for adjacent detectors and 0.1% (0.05% goal) non nearest neighbours.*	A complex requirement involving everything from the optical input to the multiplexing and the ADC! An end-to-end calibration is required to produce a cross talk map.	Yes
SRD-R9	*Maximum chop throw 4 arcmin minimum 10 arcsec*	A design requirement for the BSM. No requirement is set on the repeatability or stability of the chopping mirror. These are in fact set as requirements on the BSM and will be dealt with as a sub-system issue – see AD2.	No
SRD-R10	*The rms detector NEP variation across any photometer array <20%*	A complex requirement involving everything from the optical input through to the stability and noise of the amplifiers. An end-to-end calibration is required to produce a responsivity and noise map.	Yes
SRD-R11	*The photometer dynamic range for astronomical signals shall be 12 bits or higher*	Note the use of a number of bits here is incorrect – the dynamic range requirement is 4000. How this is encoded into bits is an implementation issue This is a design driver for the instrument. The calibration is dealt with under SRD-R14.	No
SRD-R12	*SPIRE absolute photometry accuracy shall be 15% or better at all wavelengths with a goal of 10%*	Defines the end-to-end calibration accuracy required for both point sources and extended emission. Both sub-system (filters and detectors) and instrument level calibration will be required to verify this.	Yes
SRD-R13	*The relative photometric accuracy should be shall be 10% or better at all wavelengths, with a goal of 5%*	This refers to temporal repeatability of the measurement of a known source. This will require the characterisation of the temporal stability of the system – especially the thermal stability.	Yes

SRD-ID	Requirement	Comment	Instrument level calibration?
SRD-R14	*SPIRE photometric measurements shall be linear to 5% over a dynamic range of 4000 for astronomical signals.*	This defines the usable dynamic range of the system and is assumed to go from the confusion limited sensitivity (let us say a S/N of 20 in a 1 hour observation ~0.02 mJy) to a signal 4000x higher (about 80 Jy on this definition). The instrument photometric calibration shall encompass at least this range of signal inputs.	Yes
SRD-R15	*…the overlapping sets of …detectors…should be co-aligned to within 2 arcsec on the sky (goal 1 arcsec)*	This is a design requirement that will need verifying during instrument alignment. The ultimate test will be done using the detectors themselves and a broad band FIR source.	Yes
SRD-R16	*Spectrometer optimised for point sources but with an imaging capability…*	Design driver – no calibration required	No
SRD-R17	*The FTS sensitivity shall be limited only by the photon noise from the telescope*	Note this requirement should be changed to include the photon noise from the calibrator – otherwise it is impossible to meet! This looks superficially like a design driver – however it is a complex matter and actually requires a good deal of calibration to ensure that the requirement is met.	Yes
SRD-R18	*The spectrometer dynamic range for astronomical signals shall be 12 bits or higher*	Note the use of a number of bits here is incorrect – the dynamic range requirement is 4000. How this is encoded into bits is an implementation issue This is a design driver for the instrument. There is no linearity requirement for the spectrometer – is it assumed to be the same as for the photometer? Therefore SRD-14 pertains?	No

SRD-ID	**Requirement**	**Comment**	**Instrument level calibration?**
SRD-R19	*The FTS absolute photometry at the required spectral resolution shall be 15% or better at all wavelengths with a goal of 10%.*	Defines the end-to-end calibration accuracy required for both point sources and extended emission. Both sub-system (filters and detectors) and instrument level calibration will be required to verify this.	Yes
SRD-R20	*The FTS shall be capable of making spectrophotometric measurements with a resolution of 2 cm*$^{-1}$ with a goal of 4 cm^{-1}	The minimum resolution achievable is a complex function of a variety of instrument performance factors. An end to end test will be required to characterise the achievable photon limited minimum resolution (see SRD-17 as well)	Yes
SRD-R21	*The width of the FTS instrument response function at the required resolution shall be uniform to within 10% across the FOV*	The line width could be affected by vignetting of the off-axis pixels and increased beam shear at off axis positions. This is both a design driver and needs verification at instrument level.	Yes
SRD-R22	*The maximum spectral resolution of the FTS shall be at least 0.4 cm*$^{-1}$ *with a goal of 0.04 cm*$^{-1}$ Note that the spectral resolution is defined as the FWHM of the response function assuming linear (triangular) apodisation of the raw interferogram	The maximum resolution is governed both by the physical movement of the SMEC and by any loss in fringe contrast due to beam shear and vignetting. This can only be characterised at instrument level.	Yes
SRD-R23	*The SPIRE photometer shall have a an observing mode capable of implementing a 64-point jiggle map…*	A design driver – there will be a general requirement to characterise all SPIRE observing modes but this isn't a specific driver on the instrument calibration.	No
SRD-R24	*The photometer observing modes shall include provision for 5-point or 7 point jiggle maps…*	A design driver – there will be a general requirement to characterise all SPIRE observing modes but this isn't a specific driver on the instrument calibration.	No

SRD-ID	**Requirement**	**Comment**	**Instrument level calibration?**
SRD-R25	*The photometer shall have a peak-up mode…*	A design driver – there will be a general requirement to characterise all SPIRE observing modes but this isn't a specific driver on the instrument calibration.	No

2.2 Additional Scientific Requirements

Some requirements have not been specifically identified in the SRD but will also need calibration. These are given in the table below and are given CRDS-R# identifications as new scientific requirements to be tested during instrument calibration.

ID	**Requirement**	**Comment**	**Instrument level calibration?**
CRD-SR1	The photometer and spectrometer relative response across an individual array shall be known to within TBC% with respect to any given pixel on the array.	This is the relative calibration between two detectors on a single array. It is extremely important that this is very well established in order to allow co-addition of the signal seen from a source as it is scanned or chopped across the arrays.	Yes
CRD-SR2	The relative response of the spectrometer at any wavelength within the instrument passband shall be known to within TBC% with respect to the response at any given wavelength.	One of the most important scientific projects for the FTS is the ratio of intensities of lines at different wavelengths. The relative calibration from point to point in the spectral range, including between detector bands, is extremely important.	Yes
CRD--SR3	The relative response of the photometer as a function of wavelength shall be known to within TBC% with respect to the response at any given wavelength.	The actual response vs wavelength functions for each of the photometer bands are required for the colour correction of the source intensity. The equivalent width and bandpass centroid can be derived from these functions and are also used for determining the sensitivity of the instrument.	Yes

ID	Requirement	Comment	Instrument level calibration?
CRD-SR4	The spectral out of band rejection of the filtering on the instrument shall be such as to prevent contamination of the survey data by any non-legitimate source emission.	The out of band rejection of the filters will be tested for each individual filter but will not be fully evaluated for the whole optical train except at instrument level. It is important that there are no spectral leaks in the MIR and NIR bands as bright stars etc will otherwise appear as legitimate sources in the surveys.	Yes
CRD-SR5	The instrument shall be designed so as to reduce the straylight from sources outside the field of view of the instrument to less than 5% of the legitimate background from the Herschel telescope.	This is the instrument part of the straylight budget defined in the IID-A. The control of straylight onto the detectors is done by optical filtering (see CRD-SR4); the use of “clean” optical stops and baffles and by keeping the instrument itself cold. Some assessment of the instrument’s ability to reject radiation from sources outside the nominal field of view must be made to ensure its compatibility with this requirement.	

3. BASELINE CALIBRATION AND PERFORMANCE VERIFICATION REQUIREMENTS

We can now take those SRD requirements identified as needing calibration or performance verification and break the basic requirement into the parts of the instrument performance that require verification and calibration on the ground and in flight.

This section is in two parts: in the first the calibration requirements are discussed in some more detail and the method of verification and calibration on the ground is detailed. The parameters required for calibration of the instrument data are introduced and given a nomenclature that will be used throughout this and other documentation. In the second section those calibration measurements that will need to be repeated in flight are discussed together with possible methods for carrying them out.

3.1 Ground Calibration

3.1.1 Basic test facility

We can start with the basic assumption that the ground calibration and test facility for the instrument will consist of a cryostat that will allow the instrument to be operated at temperatures and background loadings representative of flight. We can also assume that some form of optical simulator is present that presents the instrument with an optical beam representative of the Herschel telescope. The requirements on the ground calibration facility are discussed further in section 4.

3.1.2 SRD-R1/SRD-R2 Ultimate sensitivity in photometer mode

The sensitivity of the instrument is characterised by the Noise Equivalent Power (NEP) usually quoted in W $Hz^{-1/2}$. The NEP is given in terms that will be measured in practice by:

$$\mathrm{NEP} = \frac{<\delta V>}{R} \ \mathrm{W\ Hz^{-1/2}} \qquad (1)$$

Where <δV> is the voltage noise on the signal referred to the input of the JFET amplifiers measured in a bandwidth of 1 Hz – equivalent to an integration time of 0.5 seconds – and R is the responsivity of the system measured in V/W, again referred to the input of the JFET amplifiers (i.e. all electronics gains removed). Immediately we have to define at which point in the detection system we define this responsivity, and therefore the NEP. The only measure of astronomical interest is to refer this to the input of the instrument, which can then be referred to the input of the telescope as the Noise Equivalent Flux Density (NEFD) knowing the telescope area and spectral bandwidth of the instrument.

$$\mathrm{NEFD} = \frac{\mathrm{NEP_{instrument}}}{A_{tel}\Delta\lambda} \ \mathrm{W\ cm^{-2}\ \mu m^{-1}\ Hz^{-1/2}} \ ^{\blacklozenge} \qquad (2)$$

where A_{tel} is the telescope geometric area, if we assume that all coupling efficiencies are factored into the instrument NEP, and $\Delta\lambda$ is the equivalent width of the detector bandpass. This NEFD is then the

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[♦] Conversion to Janskys from W cm^{-2} μm^{-1} is given by I(Jy) = I(sensible units)*λ^2/3e-16 minimum detectable flux per beam in a 0.5 second observation for a source that uniformly fills the field of view of a detector.

In flight the instrument will be background limited by the flux of photons from the telescope, each detector will receive power from the telescope given by:

$$P_{det} = A\Omega_{inst}\, \varepsilon B_{\lambda}(T)\, \Delta\lambda\, \eta_{opt}\eta_{det} \text{ Watts} \qquad (3)$$

Here $A\Omega_{inst}$ is the throughput (also called the etendue or grasp) of the system; $\varepsilon B_{\lambda}(T)$ is the blackbody power emitted by the telescope at temperature T and emissivity ε; η_{opt} is the transmission efficiency of the instrument from the input aperture to the front of the feedhorn and η_{det} the detector quantum efficiency referred to the front of the feedhorn. The power received at the entrance to the instrument is given by:

$$P_{inst} = A\Omega_{inst}\, \varepsilon B_{\lambda}(T)\, \Delta\lambda \qquad \text{Watts} \qquad (4)$$

The NEP referred to the instrument aperture due to the photon shot noise is (ignoring the Bose-Einstein correction)

$$NEP_{pinst} = (2P_{inst}hc/\lambda)^{1/2} \text{ W Hz}^{-1/2} \qquad (5)$$

And the total NEP will be given by

$$NEP_{instrument} = (NEP_{dinst}^{2} + NEP_{pinst}^{2})^{1/2} \text{ W Hz}^{-1/2} \qquad (6)$$

Where NEP_{dinst} is the intrinsic NEP of the detector in the absence of any photon background but measured under the same operating conditions and referred to the input of the instrument.

We can measure the NEP of the detectors with a blanked off instrument – or equivalently with a blanked off detector – this can be referred to the input of the instrument by removing the instrument efficiency:

$$NEP_{dinst} = \frac{NEP_{det}}{\eta_{opt}} \text{ W Hz}^{-1/2} \qquad (7)$$

and, knowing the absolute power falling on the instrument, we can derive $NEP_{instrument}$. This can be compared to the direct measurement of the NEP using the measured noise and the responsivity referred to the instrument aperture. This can be derived from the responsivity measured at the detector unit level and knowledge of the instrument efficiency:

$$R_{inst} = \eta_{opt}R_{det} \text{ V/W} \qquad (8)$$

Two basic methods of deriving the instrument sensitivity are open to us.

1. If we can measure the responsivity, and therefore the NEP, of the detectors at unit level under the same operating conditions (temperatures and background loading) and using the same spectral input, and we can know the efficiency of the instrument from the input aperture to the

feedhorns by modelling or direct independent measurement, then we can derive the instrument responsivity. Measurement of the voltage noise on the DC output of the system with input power somewhere representative of flight then gives us the instrument level NEP directly.

We then need only measure the spectral bandpass to obtain the NEFD.

If we also know the absolute power falling on the instrument aperture (see next point) we can compare the estimated total NEP in equation (6) with that directly measured.

2. If we have an absolutely calibrated blackbody in the beam of the instrument and can measure the instrument throughput and spectral bandpass we can know absolutely the power falling on the instrument aperture. We can derive the responsivity of the instrument by varying the temperature of the blackbody (and therefore the power) and measuring the voltage response of the detectors (using V-I curves for instance). Measurement of the voltage noise on the DC output of the system with the input power set to the in flight level then gives the instrument NEP.

In practice both of these methods are likely to be used and both have their advantages and difficulties. In particular the independent measurement of the instrument efficiency, η_{opt}, is problematic. It can be obtained by comparison of the responsivity measured at detector unit level and at instrument level but this is a) non-independent and b) pre-supposes that the measurement conditions were equivalent at unit and instrument level. Alternatively we can measure the characteristics of the component parts of the optical train and combine these into an optical model of the instrument. We should attempt to measure all the relevant parameters (see table below) and cross check the end-to-end derivation against the product of the unit level derived parameters.

The Science Requirement actually refers to the detection of point sources to a 1-σ limit. Therefore we are interested in knowing the signal to noise ratio of the background limited performance of the instrument to the detected flux from a point source. The signal to noise is given by:

$$\sigma = \frac{P_{sig}\sqrt{2t}}{NEP_{instrument}} \qquad (10)$$

and the signal from a point source with a flux spectrum of S_λ W cm^{-2} um^{-1} is given by

$$P_{sig} = S_\lambda \Delta\lambda A_{tel}\, \eta_{opt}\eta_{det}\, \eta_{point} \text{ Watts} \qquad (11)$$

Where η_{point} is the coupling efficiency between the instrument and the beam pattern from the telescope. To fulfil the verification of the requirement we therefore need to measure the relative response of the instrument to a point and an extended source or, knowing the illumination pattern of the instrument on the telescope pupil, use optical modelling to calculate η_{point}.

It is pertinent to note here that we do not in practice need to know the absolute detector quantum efficiency η_{det} because we always measure the signal in terms of volts – this is converted to power at the front of the feedhorn by using the detector responsivity, which already includes the detector quantum efficiency.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-1 **Detector Absolute Responsivity** (R_{det} – V/W)	Responsivity of an individual detector referred to the input to the feedhorn. This is used to cross check the measured instrument responsivity against that predicted from the unit level calibrations.	Measured at unit level using a blackbody placed in the front of the feedhorn and any associated feed optics. Measurement of voltage response vs input power done by V-I curve method with different temperatures of the blackbody.
CRD-PAR-2 **Instrument Absolute Responsivity** (R_{inst} – V/W)	DC responsivity of each detector referred to the input to the instrument. This is the basic correction between Watts at the entrance of the instrument and volts referred to the input of the warm amplification chain. It is a function of the operating conditions (temperature; bias; background loading etc) of the detectors. It must be determined under a range of conditions to create a matrix that will allow us to predict what it will be during flight and to pick the optimum conditions for instrument operation.	Measured at instrument using a blackbody placed in the beam of the instrument beam. Measurement of voltage response vs input power done by V-I curve method with different temperatures of the blackbody. Under each loading the voltage noise is also measured to give the DC NEP as a function of position in the field of view. All detectors in all arrays can be read out simultaneously thus giving both the absolute responsivity and the relative responsivity of each pixel. The same measurement can be made with the instrument in different operating conditions.
CRD-PAR-3 **Instrument Efficiency** (η_{opt} – no units)	End-to-end transmission efficiency of the instrument optical train – allows reference of detected signal to the power received at the input aperture of the instrument	Can be deduced from absolute efficiency measurements over a given waveband of individual components and/or as a single end-to-end efficiency measurement at instrument level with known input power and detector responsivity.
CRD-PAR-4 **Channel Equivalent Bandpass** ($\Delta\lambda$ – microns)	The effective spectral width of the end-to-end optics; filters and detectors on each of the three photometer channels – used to convert from detected power to power per unit frequency (wavelength) interval.	Can be deduced from spectral relative efficiency measurements of individual components and/or as a single end-to-end efficiency measurement at instrument level – see later.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-5 **Pixel Nominal Load Noise Map** (δV_{nom} – Volts)	Measured voltage noise of the detection system for each detector in each array referred to the input of the warm amplifier chain. This is used to verify the measured NEP under nominal background loading. It is a function of the operating conditions (temperature; bias; background loading etc) of the detectors. It must be determined under a range of conditions to create a matrix that will allow us to predict what it will be during flight and to pick the optimum conditions for instrument operation.	The background into the instrument is controlled either using the shutter or by staring at a black surface of well known temperature that fills the FOV of the instrument. The noise is measured for all detectors in all arrays simultaneously. The same measurement can be made with the instrument in different operating conditions. Initially this test will done using a well calibrated external blackbody; the shutter emission will be calibrated against this blackbody in order to provide the same or similar conditions during system level testing.
CRD-PAR-6 **Instrument Throughput** ($A\Omega_{inst}$ – cm^2 steradian)	Etendue or grasp of the instrument which defines how the radiation from an extended source is coupled into the bolometers. It is required to convert from power detected to power per unit area per unit solid angle.	Difficult! In principle (Derek Martin (RD2)) the A and the Ω can be measured separately by measuring the beam pattern at the pupil and at field. See discussion in section 3.1.3.
CRD-PAR-7 **Point Source Coupling Efficiency.** (η_{point} – no units)	This is the relative amount of energy from the telescope amplitude pattern that, when the telescope is illuminated by a parallel beam, is detected by the bolometer. It is required to convert from detected power from a point source to actual input power into the instrument.	One method (perhaps the simplest?) is to compare the detected signal from an extended and a point source of the same emitted power per unit area and per unit solid angle. This could be achieved using a variable aperture in front of a hot blackbody placed at the input focal plane of the telescope simulator. Alternatively this is also given (in principle) by measurement of the relative illumination pattern of the instrument on the telescope secondary – see below.

3.1.3 SRD-R1/SRD-R2/SRD-R5/SRD-R15 Measurement of the Spatial Impulse Response Function and Instrument Throughput

The Spatial Impulse Response Function describes the shape of the angular response of an individual pixel in the bolometer arrays to a delta function or point source. The most obvious method of determining the impulse response function is to scan a point source across the field of view of an individual detector at the input focal plane of the telescope simulator. However the interpretation of this measurement will suffer from the need to have, inevitably, a source of finite extent and from any distortion of the field due the systematic behaviour of the telescope simulator. The use of a fully coherent source with a small angular spread and fully coherent phase is desirable as this can be modelled to a very high degree of fidelity and therefore de-convolution of the source from the measured response is very much easier.

Another way to determine the point spread function is to measure the response of the instrument to a point source scanned across the image of the instrument cold stop as projected outside the instrument. The Fourier transform of this response then gives the impulse response function of the instrument on the sky. Making the measurement in this fashion has the advantage that a source of reasonably extent can be used as it only has to be small compared with the size of the pupil image and the beams of all detectors can be measured simultaneously. The disadvantage of this method is that no phase information is found and so aberrations in the optics are not detected and the source will need to be carefully designed to avoid problems with straylight.

To measure the throughput of the instrument we need to measure the area of the beam at one of the conjugate planes (focal plane or pupil plane) and the angular extent of the beam at the other. To illustrate how this can be done by measurement of the response of the instrument we can derive the throughput for a single Gaussian mode as follows.

The radius of the waist (defined as the Half Width Half Maximum of the intensity pattern) of a single mode diffraction limited system at the focal plane is given by (Goldsmith):

$$w_o = \frac{2(f/\#)\lambda}{\pi} \text{ mm} \qquad (12)$$

where f/# is the focal ratio of the final optics and the wavelength, λ, defines the units (millimetres here by convention). The opening angle of the beam from a single mode feed horn – i.e. the angular spread of the illumination in the far field (at the pupil of the input optics for instance) – is given by

$$\theta \approx \frac{1}{2(f/\#)} \text{ radians} \qquad (13)$$

If we assume that the beam is circular in the far field then the solid angle subtended is given by:

$$\Omega = 2\pi\,(1 - \cos(\theta)) \qquad (14)$$

$$\approx 2\pi\,(1 - (1 - \frac{\theta^2}{2})) = \pi\theta^2$$

$$= \frac{\pi}{4(f/\#)^2} \text{ steradians} \qquad (15)$$

The area of the beam at the focal plane waist is given by:

$$A = \pi w_o^2$$

$$= \frac{4(f/\#)^2 \lambda^2}{\pi} \text{ mm}^2 \qquad (16)$$

The throughput is therefore given by:

$$A\Omega \approx \lambda^2 \text{ mm}^2 \text{ sr} \qquad (17)$$

and we have reproduced the well known result for diffraction limited throughput.

In principle measurement of the point spread function will give both the spatial extent of the intensity pattern at the focal plane – the equivalent waist radius, and, by Fourier transform, the angular spread of the beam in the far field. However, because we only measure the intensity it is not always possible to unambiguously disentangle the effects of any multi-mode response of the feedhorns and aberrations caused by misalignment or other systematic errors in the telescope simulator and/or instrument optics. It is highly desirable therefore to make a direct measurement of the angular extent of the beam directly at the instrument pupil image. This measurement also has the advantage of giving the beam filling factor compared to the full aperture of the telescope and is therefore a direct measurement of the point source coupling efficiency of the instrument.

One other science requirement that is verified during measurement of the point spread function is that on the co-alignment of the arrays. The position of the image at the output focal plane of the telescope simulator of a source placed at the input will be absolutely calibrated during the commissioning of the telescope simulator. The beam conditioning optics of the source used at the input focal plane of the telescope simulator will also be accurately calibrated. Therefore there will be absolute knowledge of the position of the input source whatever its wavelength characteristics and both the alignment of the arrays with respect to each other and their absolute alignment with respect to the telescope boresight can be verified at FIR wavelengths.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-8 **Instrument Spatial Impulse Response** (SIRF - no units)	Relative response of a pixel as a function of near beam position in the focal plane of the telescope simulator. This defines the impulse response of the instrument to a point source and is also used in determination of the instrument throughput.	The favoured method is to use an FIR laser focussed at the input focal plane of the telescope simulator. This gives a well defined illumination pattern on the telescope simulator pupil with a flat phase front. A blackbody source can also be used but this will be more difficult to interpret due to partial coherence and brightness problems. The image of the source is finely stepped over the position of the target pixel preferably in raster pattern to determine the 2-D impulse response. In principle this measurement should be made for each pixel in each array. This may prove to take too long and a minimum sub-set of pixels for which this measurement will be carried out will be identified – see also optical distortion measurement below. It is also possible that shorter cross pattern is used for some pixels rather than the full raster. Both types of measurement should be available.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-9 **Telescope Pupil Illumination Function** (PIF – no units)	Relative response of a pixel as a function of position in the pupil plane of the telescope simulator. This defines the illumination pattern of the instrument on the primary mirror of the Herschel telescope and is used for determination of the instrument throughput; the determination of the point source coupling efficiency and can be used to verify the measurement of the spatial impulse response.	A small source is scanned across the location of the image of the instrument cold stop. The method of realising this measurement using the telescope simulator is described in RD2. All pixels are measured with a single measurement – the preferred source to use here is the FIR laser however this restricts the measurement to a single channel per scan and the comparison between the laser and a black body should be done. Although it is preferred that the full 2-D area of the pupil response is explored this may be impossible due to practical difficulties with implementation. At least a cross pattern measurement should be possible.

3.1.4 SRD-R6/SRD-R8 Position of the Pixels on the Sky

The image of the detector arrays on the sky may not be perfect due to distortions introduced by the instrument optics. The arrays may also not be perfectly aligned with the telescope co-ordinate system. The FIR images of the arrays on the sky can be determined by finding the centres of the response functions of pixels at strategic locations in the field of view. In principle this measurement is already covered by the measurement of the impulse response function of these pixels as described above. However here the requirement on the knowledge of the input source characteristics are much less than required for the SIRF measurement because we are only interested in the centroids of the response functions. It will be sufficient to scan the image of a larger than point source black body across the output focal plane of the telescope simulator as long as the same source is used for each pixel position to be measured. Once the positions of the centroids of a subset of the pixels within an array have been determined, the positions of the others should be found from optical modelling and alignment measurements on the arrays and the instrument optics.

If the output of the source is stable over time and repeated operations, then this measurement can also be used to determine the relative efficiency of each of the pixels. This is useful in determining the relative efficiency of the instrument as a function of position in the instrument field of view (see also section on Relative Efficiency)

Parameter/notation/units	**Description and use**	**Outline Ground Measurement Method**
CRD-PAR-10 **Pixel Relative Position Map** ($(\alpha_{det},\delta_{det})$ - arcsec)	Relative position of the centre of the response of each pixel in each array. The position is quoted in arcsec with respect to the boresight of the instrument. This is used to reconstruct the pointing of each pixel on the sky for the construction of sky maps and the correct pointing of the telescope in flight.	A point like blackbody source is placed at the input focal plane of the telescope simulator and the image scanned is over the position of each pixel of interest. In principle this measurement should be made for each pixel in each array. This may prove to take too long and a minimum sub-set of pixels for which this measurement will be carried out will be identified. It is desirable that the source power be stable and repeatable – this will allow this measurement to be used for determination of the instrument spatial relative response function – see below.

3.1.5 SRD-R8/SRD-13/SRD-14 Crosstalk Map; Detector Frequency Response and Linearity

The detector frequency response and linearity should be characterised at unit level ahead of integration into the instrument. Indeed we will depend on this knowledge as all measurements on the PSF etc will likely need to be done with a chopped signal in order to overcome the large and potentially unstable background flux[♣]. However, the frequency response will not have been verified with the flight like electronics and harnesses and a repeat of the unit level characterisation will be necessary on at least a few pixels. This forms part of the verification of the instrument relative response requirement being the relative frequency response of the instrument.

The method is straightforward: a black body is placed at the input to the telescope simulator and the image centred on the detector of choice – one of the overlapping detectors between the three arrays. A chopper is placed in front of the black body aperture and the signal recorded as the chop frequency is varied. The relative response of the detector versus frequency is thus established. From this it is a simple matter to determine the detector time constant. The responsivity in the frequency domain is given by:

$$R_{inst}(\nu) = R_{inst}\,(1 + (2\pi\nu)^2\tau_{det}^{\;2})^{-1/2} \qquad (18)$$

where τ_{det} is given by

$$\tau_{det} = \frac{1}{2\pi\nu_{3db}} \text{ seconds} \qquad (19)$$

and ν_{3db} is the frequency at which the responsivity of the instrument falls to half of the DC responsivity R_{inst}.

While doing this test we can take advantage of the set up to test two other aspects of the instrument performance. Because we are recording data from all the pixels we will automatically have the dataset required to establish the degree of cross talk present between the detectors on an individual array. If we use instead a monochromatic source (an FIR laser) then we can also establish the degree of cross talk between different arrays. Again using a laser as a source would mean that this test could also be extended to test the linearity of the detector by inserting filters into the optical path of the laser we can attenuate it by an accurately known amount. Both the linearity and cross talk characteristics of the detection system can then be established over a wide range of signal power.

How many pixels will need to be tested in this way is not yet clear; it is probable that all of the pixels to be used for chopped observations will need to be fully characterised and, as time allows, a sub-set of the other detectors starting with the overlapping detectors across the arrays.

[♣] Especially true because we have baselined a warm telescope simulator so the instrument will see a diluted room background

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-11 **Cross Talk Map** (c_{ix},c_{iy} - no units)	For each of *i* detectors, the relative response of the detectors within the same array at position (x,y). An array-to-array cross talk map might also be necessary so each pixel tested would then have three such matrices associated with it. Used for removing spurious signals from chopped observations and ghosting from mapping observations.	A point like blackbody or laser source is placed at the input focal plane of the telescope simulator and a chopper is placed in the optical beam. The data from all detectors is recorded and analysed for the presence of signals at the known frequency – these are compared to the signal recorded at the target detector to construct the relative response matrix. In principle this measurement should be made for each pixel in each array. This may prove to take too long and a minimum sub-set of pixels for which this measurement will be carried out will be identified. It is desirable that the source power be variable over a wide range in order to detect cross talk to a level <0.05%.
CRD-PAR-12 **Detector Response Versus Input Power** (R_{linear} – no units)	For each detector this is the correction to be applied to the detected signal to refer it to the standard calibration signal. This correction removes any non-linear response of the detection system (detector plus electronics) as a function of power at the input to the instrument. The correction may be in the form of coefficients or a look up table. Several corrections may be necessary as the non-linearity of the system could be a function of chop frequency and/or operating conditions.	A point like blackbody or laser source is placed at the input focal plane of the telescope simulator and a chopper is placed in the optical beam. The power in the beam can be varied using filters with predetermined attenuation. The same measurement can be used with the instrument in different operating conditions and with different chop frequencies to complete the correction matrix.

Parameter/notation/units	**Description and use**	**Outline Ground Measurement Method**
CRD-PAR-13 **Detector Time Constant** (τ_{det} – seconds)	For each detector this is the time constant used to correct the responsivity to the DC value for time varying signals of a known frequency. Its use is predicated on the assumption that the detection system behaves as a single pole RC filter. If this proves not to be the case then a single time constant per detector may not be enough to describe the frequency response of the instrument. The time constant will depend on the operating conditions (temperature; bias; background loading etc) of the detectors. It must be determined under a range of conditions to create a matrix that will allow us to predict what it will be during flight and to pick the optimum conditions for instrument operation.	A point like blackbody is placed at the input focal plane of the telescope simulator and a chopper is placed in the optical beam. The chopper frequency is varied from near DC to several times the known or estimated 3 dB frequency of the target detector with the signal recorded at each step in frequency. The same measurement can be used with the instrument in different operating conditions to determine the relationship between operating condition and frequency response. In principle this measurement should be made for each pixel in each array. This may prove to take too long and a minimum sub-set of pixels for which this measurement will be carried out will be identified.

3.1.6 SRD-R10/CRD-SR1 Spatial Relative Responsivity and Pixel NEP Map

Once the absolute instrument DC responsivity has been established for a given set of operating conditions the responsivity of each pixel in each array can be determined relative to the nominal operating point. Variation in the instrument responsivity as a function of position might be due to a number of effects – detector responsivity; vignetting; change in the instrument bandpass as a function of position; change in the optical efficiency as a function of position etc. Whilst the measurement of the relative DC responsivity is established by the load curve measurement using a source that fills the field of view as described above, many of the other possible effects can only be tested using a correctly conditioned input beam. The measurement used for the determination of the pixel positions on the sky will also give a relative response versus position in the focal plane if the source used is sufficiently stable and repeatable.

To determine the NEP as a function of position in the focal plane we only need then to measure the noise under the same set of operating conditions as used for the determination of the DC responsivity. The Pixel Nominal Load Noise Map (see above) will also be used to cross check the measured NEP.

Parameter/notation/units	**Description and use**	**Outline Ground Measurement Method**
CRD-PAR-14 **Spatial Relative Responsivity** (r_{xy} – no units)	Relative response of each pixel in each array with respect to a nominal pixel position and set of operating conditions. Whilst this may seem superfluous as we already have the absolute instrument responsivity as a function of position in the FOV, the determination of the absolute responsivity will be done, by necessity, using a source that fills the FOV uniformly. The spatial relative responsivity is the relative point source response of the instrument as a function of pixel position in the FOV. This is used to flat field the instrument image frames to allow co-addition across different pixels.	A point like blackbody source is placed at the input focal plane of the telescope simulator and the image placed at the position of each pixel of interest and the signal recorded. In principle this measurement should be made for each pixel in each array. This may prove to take too long and a minimum sub-set of pixels for which this measurement will be carried out will be identified. The source power must be stable and repeatable. This measurement could be combined with the measurement of the pixel relative position map.

3.1.7 CRD-SR2/CRD-SR3/CRD-SR4 Relative Spectral Responsivity; Channel Central Wavelength and Bandpass; Out of Band Rejection

The spectral response of each of the instrument channels is the product of the spectral response of the detectors; the filter spectral transmission profile and the spectral transmission efficiency of the optics. Whilst the first two of these can be, more or less, determined at unit level, the optics will not be verified in the FIR until the instrument is complete. Therefore, the combination, and any effects caused by such a combination, of all three must also be characterised at instrument level. The measurement of the spectral relative efficiency will be done by the use of an external spectrometer with a black body input source. The output of the spectrometer will be focussed at the input focal plane of the telescope simulator and the image placed at the position of each pixel to be measured in turn. At least a subset of pixels will be measured to the highest possible spectral resolution and good signal to noise to verify that there are no problems with channel fringing or other unaccounted for spectral features present. Other pixels may also be characterised at a lower resolution and/or with lower signal to noise as a confidence check.

Once the relative spectral response of the instrument, $f_{inst}(\lambda)$, has been determined the bandpass or equivalent width of each channel is given by:

$$\Delta\lambda = \int_{\lambda l}^{\lambda u} f_{inst}(\lambda)d\lambda \qquad (20)$$

And the central wavelength is given by

$$\lambda_c = \frac{\int_{\lambda l}^{\lambda u} \lambda f_{inst}(\lambda)d\lambda}{\int_{\lambda l}^{\lambda u} f_{inst}(\lambda)d\lambda} \qquad (21)$$

Here λl and λu are the lower and upper wavelength limits over which the external spectrometer operates. It is highly desirable that the spectrometer; telescope simulator and any filtering in the ground test system are able to operate at wavelengths well below and above the nominal bandpass of the instrument in order to verify the cleanliness of the instrument spectral bandpass. It is possible that the FIR laser could also be used to check the out of band rejection of the instrument in a semi-quantitative manner. Another method of checking the out of band rejection is to use a bright optical/NIR source with a suitable highpass (short wavelength) optical filter.

The resolution required for the test spectrometer should be such as to find any possible sources of channel fringing within the instrument. We do not expect efficient interference to occur in the instrument at equivalent resolving powers greater than a few hundred and the narrowest features present in the filters will be at much lower resolution than this. Therefore an external spectrometer with a resolution of several hundred at the longest wavelength of interest should be sufficient.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-15 **Spectral Relative Responsivity** ($f_{inst}(\lambda)$ – no units)	Relative response of each pixel in each array as a function of wavelength. This is used to colour correct the measured fluxes of objects with known or assumed continuum spectra. It is also used to determine the equivalent width and central wavelength of each channel. In the spectrometer channels the spectral relative responsivity is used to spectrally "flat field" the measured source spectra. It is especially important that this parameter is accurately determined for each spectrometer pixel as all are used for taking astronomical spectra.	A test spectrometer is used to feed the input focal plane of the telescope simulator. The output of the spectrometer should be as near to a point source as possible. The image of the test spectrometer output is placed at the position of a pixel and the wavelength (or position if an FTS) scanned. This measurement should be done at high (R~few hundred-thousand) resolution and with good s/n (~1000 per spectral bin) in order to accurately determine the relative spectral response function of the instrument. Each pixel in the spectrometer channel must be measured to high accuracy; only the overlap pixels in the photometer arrays need be measured with high accuracy. Other pixels maybe measured at low resolution if time allows.

3.1.8 SRD-R13 Temporal Relative Responsivity

The final aspect of the relative responsivity requirement that requires verification is the requirement to be able to make repeated observations of the same source and achieve the same answer in terms of the flux measured. In order to achieve this the detection system must be intrinsically temporally stable and we must have a method of determining its stability both on ground and in flight. One method of doing this is to measure the signal from a known and stable source with the instrument in a known operating condition at intervals that sample a wide frequency range. This will show whether there are changes in the instrument responsivity over time and their characteristic frequencies. On the ground this might be achieved by placing the instrument into a given stable operating condition – photometer scan mode say – and using a stable external source (it doesn’t need to be of known output, just very stable and repeatable) to make measurements of the instrument relative response at intervals of a few minutes up to, say, 24 hours. This measurement will be a verification of the intrinsic stability rather than a calibration and no calibration parameter is derived.

In flight this is more difficult as it may not always be possible to acquire a calibration target at convenient times. Therefore, we have incorporated a calibration source into the design of the instrument that will illuminate all pixels in both the spectrometer and photometer channels. We require that this calibration source be characterised during ground testing so that its performance can be verified and its output calibrated against a known external reference source. This can be done by operating the calibrator during the calibration of the DC responsivity of the instrument to give a small amount of extra input power onto the detectors. The delta signal seen on top of the known load gives a correlation between equivalent power seen at the entrance to the instrument and the set point for the calibrator. The response at each detector may be different, as the calibrator may not be seen equally well by all detectors in all arrays. The stability of the calibrator output is therefore important and this must be tested at the same time as the detection system stability.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-16 **Calibrator Equivalent Power** (CR – W per step)	Calibration between the operating set point of the internal calibrator and the signal seen on the detectors under nominal operating conditions. This can be converted to an equivalent flux referred to the input aperture of the instrument. The calibrator is used for testing the stability of the detection system and this calibration will be used to determine the optimum operation of the calibrator in flight. Several types of calibration may be necessary to give maximum flexibility to the method of in flight calibration.	In order to absolutely calibrate the equivalent flux from a small step in the calibrator output a blackbody can be placed in the beam of the instrument and set to give the same flux as used for the DC responsivity calibration. The instrument is set to its nominal operating condition (bais; temperature etc) and the calibrator cycled between on and off with a small output step To provide a stable output the calibrator may have to be driven at the upper end of its temperature range, therefore this step may be done on top of a DC pedestal. The net DC signal will be arranged to be the same by reducing the load from the external blackbody. This can be repeated for different flux levels and calibrator and detector operating conditions.

3.1.9 SRD-R12 Photometer Absolute Radiometric Accuracy

The ultimate photometric accuracy in the photometer channels depends on all the parameters discussed above and the errors generated in their measurement. The statistical errors can be minimised using long integration times during ground testing and systematic errors minimised by design. However, systematic errors cannot be fully eliminated and we should not suppose that the ground test has generated an unambiguous absolute calibration of the instrument. Additionally, some aspects of the Herschel system level performance (pointing accuracy and reconstruction; telescope effective area etc) will effect the achievable absolute photometric accuracy and these will not be known or fully tested until Herschel is in orbit. Therefore, while there will be a verification of the potential for absolute photometry with SPIRE during ground testing, the ultimate test will be done in flight using a number of calibration targets with known spectral characteristics (see later).

The one aspect of instrument level performance that may place a fundamental limit on the photometric accuracy is the stability and repeatability of the instrument responsivity. This in turn is a complex function of the temperature stability of the various stages and the electronics performance. At instrument level we can characterise the impact of temperature drifts in the FPU and the electronics but we will only be able to qualitatively assess the absolute system stability. See also the discussion on the calibrator stability; this too is important as it will be used to monitor and correct any drifts in internal responsivity.

3.1.10 CRD-SR5 Rejection of Radiation from Outside the Field of View

The optical design of the instrument is intended to prevent radiation from outside the field of view of the two sub-instruments from reaching the detectors directly or via any of the mirrors in the optical chain. This design must be verified and an attempt made to identify if there are any straylight paths within the instrument for sources outside the instrument FOV.

Testing this will be very difficult

3.1.11 SRD-R17 FTS Sensitivity – determination of Zero Path Difference Position

The photometric sensitivity of the FTS when it is stationary and at zero path difference (ZPD) is governed by the same parameters as discussed for the photometer. These parameters will be measured in the same way with the additional step of determining the position of the scanning mirror where ZPD occurs. This can be done using the internal spectrometer calibrator in one entrance port whilst viewing a cold black surface in the other (either the shutter or viewing an external black surface that fills to field of view of the spectrometer). The Spectrometer Mirror Mechanism (SMEC) will be stepped across the central maximum of the interferogram and the position at which the signal reaches a maximum is then the ZPD position. Once the ZPD position has been determined the SMEC will be set to that position during all photometric calibration measurements described above.

Parameter/notation/units	**Description and use**	**Outline Ground Measurement Method**
CRD-PAR-17 **Zero Path Difference Position (ZPDP – commanded position in ADU)**	This is the position in the SMEC scan range at which the path length in the two spectrometer arms is exactly the same. It should be the same in both spectrometer channels (let's hope). It is used to determine where to set the SMEC for all photometric calibration measurements and so that the correct scan length can be input for each desired resolution.	A cold black body is placed in the sky port of the FTS that complete fills the spectrometer FOV (either external black body or the shutter). The spectrometer calibrator is set to maximum output and allowed to stabilise. The SMEC is stepped from a known position (home would be a reasonable start) to some other towards the known ZPD direction and back again then to the next position and back and so on until the ZPD has definitely been transited. The data from the arrays is collected continuously at a high rate (16 Hz) during this operation. The stepping frequency should be at least 1 Hz. The measurement should be repeated with the calibration source cold and the external black body set to a known temperature to ensure that the ZPD position is the same in both paths through the spectrometer.

3.1.12 SRD-R17/SRD-R20/SRD-R22 Velocity Stability; Minimum and Maximum Achievable Resolution

The stationary responsivity of the bolometer arrays is only one aspect of the FTS sensitivity. The baseline operating mode for the FTS will be to scan the SMEC continuously whilst taking data from the detector arrays. The velocity stability of the SMEC during scanning will be important in determining both the ultimate sensitivity of the FTS and the minimum achievable resolution of the FTS in scan mode.

One method of determining the velocity stability – and the basic test of the FTS spectroscopic performance – is to feed the FTS with a laser line and to scan the SMEC over its full range of movement. Because the spectral input is a delta function the measured signal should be a pure cosine. The expected signal can be well modelled and any deviations from the expected signal due to velocity instabilities or other problems can be relatively easily identified. This test requires that the laser source shall be stable over short and medium timescales (0.1-25 Hz is the nominal detection band of the detectors for instance). The fringe contrast of the cosine as a function of SMEC position will show whether the maximum specified resolution is actually achievable and whether problems are occurring due to beam shear etc within the instrument.

Another test of the velocity stability of the FTS is to measure the spectrum of an accurately known black body in the absence of the nulling from the spectrometer calibrator. The ability to reconstruct the input spectrum under these circumstances is critically dependent on the velocity stability of the mirror movement. The test can be repeated with the spectrometer calibrator set to various levels of output. This directly calibrates the calibrator output and determines the ability of the calibrator to null the telescope background in flight.

Both these tests should be carried out under a variety of operating conditions for both the SMEC and the detectors. The spectrometer calibrator may be capable of providing the correct background loading on the detectors during tests with the laser. This is important as the frequency response of the detectors is one of the determining factors in the minimum achievable resolution.

Parameter/notation/units	Description and use	Outline Ground Measurement Method
CRD-PAR-18 **SMEC Velocity Stability** (δV - µm/s/rt(Hz))	This is not a direct calibration parameter but rather verification that the FTS is capable of achieving the required sensitivity and minimum resolution.	In one test a laser line is focussed onto one of the spectrometer pixels and the SMEC is scanned over its full range of movement. Several wavelength lines are required to cover the range of the two spectrometer channels. The laser must be stable enough that the velocity instability can be distinguished from any source instability. A second test that will determine stability of the velocity is to measure the interferogram of a black body source placed in the sky port of the FTS that completely fills the spectrometer FOV (either external black body or the shutter). In this test the spectrometer calibrator is set to zero output.
CRD-PAR-19 **Spectrometer Calibrator Equivalent Power** (SCR – W per step)	Calibration between the operating set point of the spectrometer internal calibrators and the flux entering the aperture of the instrument. This is used to absolutely calibrate the measured spectra in flight.	In order to absolutely calibrate the equivalent flux from the calibrator output a blackbody can be placed in the sky port of the FTS. The SMEC is scanned over a short range about the ZPD. Each of the spectrometer calibrators is stepped over its full range of operating points. When the spectrum is nulled the input power from the calibrator and external source are matched. This test can be repeated for different temperatures of the external blackbody and different mirror scan velocities.

Parameter/notation/units	**Description and use**	**Outline Ground Measurement Method**
CRD-PAR-20 **Fringe Contrast Map** (FCM - no units)	The fringe contrast on a delta function input spectrum may vary over the scan range of the mirror mechanism. A map of the variation in contrast will be used to correct the measured interferograms. In principle this must be determined for each pixel in the spectrometer arrays.	Same test as for velocity stability using a laser line focussed onto a single pixel. Different lines will be used to check for any variation with wavelength. This also tests the maximum achievable spectral resolution. This test will be repeated for as many pixels in the spectrometer arrays as practicable.

3.1.13 SRD-R21 Spectrometer Spectral Response Function

The spectral response function of an FTS spectrometer depends critically on the apodisation technique used in the treatment of the interferogram before conversion to the spectral domain. We have assumed that the requirement refers to the FWHM of a linearly apodised interferogram of a spectral delta function input after conversion to the spectral domain. To determine how this varies with position in the instrument FOV the laser will be focussed onto each pixel in the spectrometer array in turn and the SMEC scanned over its full range of movement. No extra measurement is required as the fringe contrast map measurement provides the data set to evaluate the spectral response function.

Parameter/notation/units	**Description and use**	**Outline Ground Measurement Method**
CRD-PAR-21 **Spectral Response Function** (SRF - no units)	The relative response of each pixel in the spectrometer to a spectral delta function input in the spectral domain. This is used to determine the sensitivity of the instrument to spectral lines and will be used to deconvolve the instrument function from measured spectra.	Same data as obtained for the Fringe Contrast Maps.

3.1.14 SRD-R19 Spectrometer Absolute Radiometric Accuracy

The same arguments about the validity of ground testing the absolute radiometric accuracy apply to the spectrometer as were discussed above for the photometer. Only the in-flight calibration will determine the real absolute photometric accuracy achievable.

Two aspects of the instrument performance that will affect the absolute photometric accuracy, and that will be capable of characterisation on the ground, are the stability of the calibrator and the repeatability of the SMEC velocity control. The spectrometer calibrator is designed both to null the black body spectrum from the telescope and to provide a reference comparator that has been accurately calibrated on the ground. The repeatability and stability of the calibrator output will therefore largely determine the accuracy to which an astronomical signal will be calibrated in flight.

The repeatability of the mirror scan velocity will also have an impact on the ultimate photometric accuracy of the low resolution spectra from the spectrometer. Whilst we can know what the velocity of the mirrors actually was during a scan, the effect of the induced phase changes from velocity instability within a scan or from scan to scan are a highly complex matter. Our ability to remove the effects of velocity instability and non-repeatability will depend critically on an accurate knowledge of the transfer function of the instrument in frequency space. This can be assessed and characterised on the ground but it, too, is a complex function of the detector operating conditions; optical performance and stability of the detector electronics chains. Only when we are in flight will we be able to characterise these parameters in a meaningful way.

While there are no new parameters to be measured for this calibration requirement, it does imply that the calibrator output must be characterised to ensure its stability – i.e. the measurement of the calibrator equivalent power must be a) carried out over a contiguous typical operating time period to look at drift and b) repeated over a long time base to characterise the calibrator output repeatability.

Similarly, whilst the SMEC velocity stability will be assessed directly, we also need to make an assessment of the repeatability of the velocity over a number of operations.

3.2 In orbit calibration

Single Pixel
This lot could be done for both channels with SMEC set to ZPD

Beam profile – for key pixels – full 2-D map using bright point source. Neptune or bright quasar (10-100 Jy)
All pixels x-y scans – could be done in scan mode to get relative impulse response and gain map and pixel position.
Long dark noise measurement to characterise the 1/f noise spectrum of the system – repeat with chopper on to test for microphonic input – repeat in scan mode across clean area of sky.
All long measurements – 10’s of minutes to an hour to look for 1/f knee.

Point Source Photometry
Again for both channels with SMEC set to ZPD

V-I curve to check loading from telescope – tells us background – need to set optimum bias.
Verify bias by doing photometry on bright source and varying bias
Then repeat on a weak source to check this is also the best bias in all circumstances
Again could do this in scan mode for efficiency – need to repeat at various scan speeds at each bias setting to set up the optimum operating point for the scan mode mapping.

Chopped measurement with correct offset and throw on moderately bright point source with variable frequency from 0.5 to 5 Hz (TBC)

Check of pointing with respect to telescope co-ordinate system – scanned measurement for crude test – then chopped seven point jiggle – tests co-alignment at the same time.

Use a chopped raster measurement to determine the optimum position for chopped observations with different chop throws – finds best chop amplitude.

Do the same measurement in jiggle – slower chopping – and chop between aligned rows…

Routine operation of the calibrators to test for responsivity drifts psuedo random intervals through orbit.

Flux calibration done per mode
Will be done with astronomical objects – planets; asteroids; stars etc
All done in seven point mode as primary calibration.

Then use these calibrators to calibrate scan mode as a separate exercise. Scan at different rates; look at how accurately the telescope can be repointed; accuracy of pointing during scanning.

64-point jiggle done on a point source – repeated with source placed in different parts of the field to check the ability to recover the flux from any position in the field.

Make a nodded measurement on moderate point source.

Spectrometer Calibration

As implied above need initial set up measurement of where the ZPD is – can do this in step and look mode most accurately (?) with calibrator off looking at bright continuum source and chop on/off the source as the SMEC is stepped across the maximum in the interferogram or can do it in scan mode with just the telescope background or partially nulled telescope background. Doing the measurement in scan mode on the telescope should be done anyway as all pixels will respond in this measurement and the position of the ZPD for each of the pixels can be verified.

Once the ZPD is found we can set this position and carry out all the photometric and beam measurements listed above. Can we do all detectors together – i.e. run both sets of detectors using the full data capacity we have available? Check this, if not then we would do it serially – check how long this takes.

Next we need to look at the SMEC performance for velocity stability and beam shear/vignetting – this can only be done on a source with strong lines – need to identify suitable source(s). Run though the set of velocities established on the ground to find the optimum operating point.

We may also need to look at operating the SMEC with a different set of control loop parameters in flight. How do we find the best operating point for these? Could be just done with the engineering mode and confirmed on the strong line source – if so it is covered by the verification requirements not calibration.

Once a line source(s) has been identified and the interferogram taken all other performance parameters should fall out.

We will want to place the line source in each of the pixels in the FOV to establish the off axis performance of the instrument in flight.

3.3 AOT Verification

Having discussed the ground and flight calibration needs we have to go on here to look at the AOTs described in the OMD and discuss what calibration measurements are needed to verify these on the ground and in flight (some overlap with previous section?). This will place requirements on the ground cal facility.

4. GROUND CALIBRATION FACILITY OUTLINE REQUIREMENTS

Evaluation of the ground test requirements laid out in section 3 leads to the following requirements on the ground calibration and test facility.

Req. ID	**Description**	**Source/reason**
CRD-GT-R1.	A cryostat is required that will house the instrument and provide the same mechanical; electrical and thermal interfaces as presented by the Herschel cryostat	Needed to provide correct operational environment – no direct calibration requirement
CRD-GT-R2.	A telescope simulator is required to present the instrument with a beam that is optically identical to that of the Herschel telescope.	CRD-PAR-6 – Instrument Throughput CRD-PAR-8 – Instrument Spatial Impulse Response
CRD-GT-R3.	A continuum or monochromatic point like source placed at the input focus of the telescope shall be well focussed at an image plane at the same relative position to SPIRE as will be provided by the Herschel telescope.	CRD-PAR-7 – Point Source Coupling Efficiency
CRD-GT-R4.	The telescope beam should be capable of being placed and focussed correctly on each pixel within the SPIRE FOV. It is not required that the beam from the telescope simulator shall simultaneously fill the SPIRE FOV – i.e. it may be steered from pixel to pixel.	CRD-PAR-6 – Instrument Throughput CRD-PAR-10 – Pixel Relative Position Map CRD-PAR-14 – Spatial Relative Responsivity CRD-PAR-20 – Fringe Contrast Map
CRD-GT-R5.	It is desirable that the input FOV of the telescope simulator is large enough that an extended source that instantaneously fills the beam of a single pixel may be used.	CRD-PAR-7 – Point Source Coupling Efficiency
CRD-GT-R6.	The telescope simulator must be capable of scanning stepwise the image of a point like coherent source across the beam of any pixel in the SPIRE FOV. The stepsize shall be small enough to provide an accurate measurement of the spatial response of the instrument – i.e. at least 1/10 of the FWHM at 200 µm.	CRD-PAR-6 – Instrument Throughput CRD-PAR-8 – Instrument Spatial Impulse Response CRD-PAR-10 – Pixel Relative Position Map
CRD-GT-R7.	It is desirable that the beam from the telescope can be scanned continuously across the beam of single pixel in the SPIRE FOV.	Needed to replicate scan mode AOTs – set a requirement to do this
CRD-GT-R8.	The photon background falling onto the entrance aperture of the instrument shall be no greater than that expected from an 80-K 4% emissive surface during any measurement set up – i.e. it shall be at least representative of that from the Herschel telescope in flight	CRD-PAR-5 – Pixel Nominal Load Noise Map CRD-PAR-12 – Detector Response Versus Input Power CRD-PAR-13 – Detector Time Constant
CRD-GT-R9.	It shall be possible to have the instrument operate in	CRD-PAR-17 – Zero Path Difference

Req. ID	Description	Source/reason
	a low background environment – i.e. dark.	Position Also required to trouble shoot detector/microphonic/JFET performance
CRD-GT-R10.	A source shall be provided that instantaneously illuminates the entire SPIRE FOV. This source shall be highly emissive in the FIR and Sub-mm and shall be of known, controllable temperature, and known emissivity. It is not necessary to feed this source to the instrument through the telescope simulator.	CRD-PAR-2 – Instrument Absolute Responsivity CRD-PAR-3 – Instrument Efficiency CRD-PAR-5 – Pixel Nominal Load Noise Map CRD-PAR-16 – Calibrator Equivalent Power CRD-PAR-17 – Zero Path Difference Position CRD-PAR-18 – SMEC Velocity Stability CRD-PAR-19 Spectrometer Calibrator Equivalent Power
CRD-GT-R11.	An image of the entrance pupil of the telescope simulator shall be made accessible to allow a point like source to be scanned across the pupil location to make measurements of the instrument beam falling on the telescope secondary mirror.	CRD-PAR-6 – Instrument Throughput CRD-PAR-7 – Point Source Coupling Efficiency CRD-PAR-9 – Telescope Pupil Illumination Function
CRD-GT-R12.	A spectrometer shall be provided external to the instrument and fed to the instrument through the telescope simulator. This spectrometer shall have a resolution of at least 500 at 250 µm; a wavelength coverage of at least 200 to 700 µm and shall have a continuum source at its input.	CRD-PAR-4 – Channel Equivalent Bandpass CRD-PAR-15 – Spectral Relative Responsivity
CRD-GT-R13.	A method of measuring the out of band rejection of the instrument shall be provided.	CRD-SR4 – Out of Band Rejection
CRD-GT-R14.	A method of evaluating the off axis straylight rejection of the instrument shall be provided.	CRD-SR5 – Rejection of Radiation from Outside the FOV
CRD-GT-R15.	A mono-chromatic source with a line width very much narrower than 0.04 cm^{-1} (at least 1/100) shall be provided that shall be fed to the instrument through the telescope simulator. This source shall have lines from 100 to 700 µm.	CRD-PAR-6 – Instrument Throughput CRD-PAR-7 – Point Source Coupling Efficiency CRD-PAR-8 – Instrument Spatial Impulse Response CRD-PAR-18 – SMEC Velocity Stability CRD-PAR-20 – Fringe Contrast Map CRD-PAR-21 – Spectral Response Function
CRD-GT-R16.	A chopper shall be available that can modulate the signal entering the telescope simulator. The frequency of the chopper must be accurately known (within 1%) and variable from 0.5 to 5 Hz. It is	CRD-PAR-11 – Cross Talk Map CRD-PAR-12 – Detector Response Versus Input Power CRD-PAR-13 – Detector Time

Req. ID	**Description**	**Source/reason**
	desirable to have the ability to chop between two sources of different temperature (i.e. hot ~few hundred K and cold LN_2 77 K)	Constant
CRD-GT-R17.	A method of commanding and receiving data from the instrument that accurately mimics the in-flight command and data management system shall be provided. It shall be capable of simulating actual in-flight operations and allowing astronomical observations to be simulated in the ground test facility.	Required to simulate in-flight operations and test AOTs etc – add this as requirement.