SPIRE

Operating Modes for the SPIRE Instrument

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Change Record

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1.0	30/11/1999	Issued Prior to Warm Electronics Review
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3.1	Oct. 2004	Working version for revisions mainly to Chapter 5
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4.0	August 1 2008	Version for Herschel Ground Segment Readiness Review, updated by M. Griffin and S. Leeks

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List of Acronyms

AME	Absolute Measurement Error
AOCS	Attitude and Orbit Control System
APE	Absolute Pointing Error
kbs	Kilo-bits per second
BSM	Beam Steering Mechanism
CDMS	Command and Data Management System (on Spacecraft)
DPU	Digital Processing Unit
FOV	Field of View
FPU	Focal Plane Unit
FTS	Fourier Transform Spectrometer
HIFI	Heterodyne Instrument for Infrared
HSC	Herschel Science Centre
IID-A	Instrument Interface Document part A
IID-B	Instrument Interface Document part B
IRD	Instrument Requirements Document
MOC	Mission Operations Centre
OBS	On Board Software
PACS	Photodetector Array Camera and Spectrometer
PDE	Pointing Drift Error
POF	Photometer Observatory Function
RPE	Relative Pointing Error
S/C	Space Craft
SOF	Spectrometer Observatory Function
SPIRE	Spectral and Photometric Imaging Receiver
TBC	To Be Confirmed
TBD	To Be Determined

List of Symbols

Symbol	Definition	Page
d_1	Angular distance between adjacent raster points in a line	13
D_1	Angular length of a line scan	14
d_2	Angular distance between lines in a raster or scan map	13
$f_{\rm chop}$	BSM chop frequency	20
A, B	Telescope nod positions	12
L, R	BSM chop positions	12
M	Number of raster positions along one line of a raster map	13
N	Number of lines in a raster or scan map	13
n	Number of positions observed in a jiggle map	25
$N_{\rm chop}$	Number of chop cycles carried out at each jiggle position (or each nod position in the case of point source photometry)	15
$N_{\rm jigcyc}$	The number of jiggle cycles in an observation	16
$N_{\rm jigpat}$	Number of jiggle patterns/nod position in 7-point mode	23
$N_{\rm jigpos}$	Number of separate BSM positions in a jiggle cycle	15
$N_{\rm nod}$.	Total number of nod cycles to be carried out in an observation.	17
$t_{\rm chop}$	Time for one complete chop cycle	15
$t_{\rm jigcyc}$	Total time taken for a complete jiggle cycle	16
$t_{\rm nod}$	Total time per nod cycle	16
$t_{\rm scan}$	Total time for a scan map observation	17
x, y	Linear (distance) coordinates of a point on a detector array with respect to the geometrical centre of the PSW array X and Y directions	10
α	Angle between the celestial RA axis and the spacecraft Z axis	10
$\Delta t_{\rm rast}$	The total time spent in moving the telescope between raster positions	17
$\Delta t_{\rm chop}$	Time between the start of a chop motion to a new position and the instant at which data at the new position are deemed valid	15
$\Delta t_{\rm jig}$	Time taken to move from one jiggle position to the next	15
$\Delta t_{\rm line}$	Time taken for repointing by angle d_2 between lines during a scan map	17
$\Delta t_{\rm motion}$	Time between the start of a telescope slewing motion and the instant at which the new telescope position is deemed to have been reached	14
$\Delta t_{\rm nod}$,	Time between the start of a nod motion and the instant at which the new telescope position is reached	16
$\Delta t_{\rm step}$	Time taken for for repointing by angle d_1 along a line during a raster map	17
$\phi_{\rm nom}$	Nominal value of $\phi_{\rm scan}$	30
$\phi_{\rm scan}$	Angle between the telescope scan direction and the positive Y axis.	30
$\Delta\theta$	Angular distance moved by the telescope	14
$\Delta\theta_{\rm chop}$	BSM chop angle (normally along Y axis)	15
$\Delta\theta_5$	Angular offset for 5-point (POF 7) observations	32
$\Delta\theta_7$	Angular offset for 7-point observations	23
$\Delta\Theta_{\rm YP}$, $\Delta\Theta_{\rm ZP}$	Position of the centre of the SPIRE PSW array with respect to the centre of the Herschel focal plane	11
$\Delta\Theta_{\rm YS}$, $\Delta\Theta_{\rm ZS}$	Position of the centre of the SPIRE PSW array with respect to the centre of the Herschel focal plane	11
$\Delta y_{\rm chop}$	Chop distance in the array focal plane	19
$\theta_{\rm Y}$, $\theta_{\rm Z}$	Angular coordinates of a point on a detector array with respect to the geometrical centre of the PSW array X and Y directions	25
$\dot{\theta}$	Telescope angular scan rate	14
$\dot{\theta}_{\rm line}$	Steady telescope scan speed during a scan map.	17
$\ddot{\theta}$	Telescope angular acceleration rate	14
$\Theta_{\rm Y}$, $\Theta_{\rm Z}$	Angular coordinates of a point on the sky with respect to the centre of the Herschel focal plane	11

Applicable Documents

AD 1: IID-A SCI-PT-IIDA-04624, Issue: 3.0, 1 July 2002

AD 2: Instrument Requirements Document (IRD), SPIRE-RAL-N-0034, Issue: 1.2, 20 May 2003

Reference Documents

RD 1: SPIRE Design Description Document, SPIRE-RAL-PRJ-000620, Issue 2.0, 15 May 2003

RD 2: SPIRE PACS Parallel Mode Observers' Manual , HERSCHEL-HSC-DOC-0883, Version 1.1 04-June-2007

RD 3: Herschel Pointing Modes, SCI-PT-RS-07725, 25 May 2002 (Annex 4 to IID-A)

RD 4: Scientific Mission Planning System: Pointing Modes, HERSCHEL-HSC-DOC-624, Jon Brumfit, Issue 1.11, 16 April 2007

RD 5: SPIRE FTS Mapping Modes, SPIRE-RAL-NOT-002801, Ed Polehampton, Issue 1, 16 Jan. 2007

RD 6: SPIRE Observers' Manual, HERSCHEL-HSC-DOC-0789, version 1.2 11-Sep-2007

RD 7: Calculation of Important Parameters for SPIRE Scan-map Observations, Tim Waskett, V1.0, April 2007

1. INTRODUCTION

This document describes the expected operating modes for the SPIRE instrument on Herschel. It gives a detailed description of the operations required to implement each operating mode in order to place requirements on the components of the SPIRE instrument other than the cold FPU – i.e. the warm electronics; on-board software and ground segment. The underlying assumption in this document is that the configuration of the instrument cold FPU is as defined in AD2, the *SPIRE Instrument Requirements Document* (IRD). This document describes how the sub-systems defined in the IRD are to be operated; it is not intended to place further requirements on the cold FPU sub-systems.

Section 2 gives the assumptions underlying the description of the operating modes and the expected conditions for the satellite operations. Section 3 describes the observatory functions that are required to implement the SPIRE observations. Section 4 deals with possible degraded instrument operation due to sub-system failure.

2. MISSION ASSUMPTIONS

2.1 Herschel and SPIRE

The Herschel mission is dedicated to observing the cosmos at wavelengths from 55 to 700 µm. It consists of a 3.5-m telescope at a temperature of 80 K with a suite of three cold focal plane instruments. SPIRE instrument is one of three focal plane instruments for Herschel. It will make observations in the 200-670 µm band using bolometric detectors. The focal plane unit of SPIRE is operated at cryogenic temperature (~ 5 K) and the detectors are operated at ~300 mK. The instrument is described in RD 1 (*SPIRE Design Description Document*).

SPIRE consists of two sub-instruments:

Photometer: A three band imaging photometer using three separate bolometer arrays with fixed optical band pass filters with resolution of about 3. This will simultaneously image a 4 x 8 arcmin field of view onto three bands centred on 250, 350 and 500 µm. A beam steering mirror will be used to move the image of the sky over the arrays to chop the field view of the instrument onto the sky background close to the object of interest and to give complete spatial sampling of the field of view by stepping the image by fractions of the Airy pattern diameter.

Spectrometer: An imaging Fourier Transform Spectrometer (FTS). This uses two bolometer arrays to give spectrally resolved images of a small (~2.6 arcmin diameter) area of sky (the unvignetted footprint for a single pointing is slightly smaller, ~ 2 arcmin.). The two bolometer array have nominal spectral bands of 194-324 and 316-672 µm. The maximum resolution of the instrument will be about 0.04 cm^{-1}. The spectrometer shares the input optics to the instrument with the photometer. This includes the beam steering mirror which can be used to step the image across the arrays to give full spatial sampling of the field of view.

The photometer and spectrometer will not be operated at the same time.

2.2 Other Herschel Instruments

There are two other instruments on Herschel:

HIFI (The Heterodyne Instrument for Infrared): A heterodyne spectrometer to give very high resolution spectroscopy over the 2700 to 480 GHz frequency band.

PACS (Photo-detector Array Camera and Spectrometer): A broadband imaging photometer and medium resolution imaging spectrometer operating over the 55 – 200 µm waveband.

The HIFI cold FPU and local oscillators will be switched off during all SPIRE observations. It is possible that SPIRE will be used to take simultaneous images with the PACS instrument, with PACS and SPIRE operating in PARALLEL mode (see RD 2). The SPIRE arrays will also be sampled during telescope slews, providing serendipitous data. There are no plans for the SPIRE ICC to support analysis of these data - but they will be archived in case they may be of any scientific value in the future.

2.2.1 Mission Operations

The following assumptions are made about how Herschel/SPIRE will be operated:

- Herschel will operate autonomously with no real time monitoring of the telemetry on the ground, except during the data transfer periods.
- Herschel will be out of ground contact for 21 out of every 24 hours.
- All instrument data will be passed into the satellite on board solid state recorders at an average rate of no more than 130 kbs averaged over 24 hours. The instantaneous data rate can exceed this value.
- When the spacecraft is out of ground contact, the instrument will be responsible for its own health and safety monitoring and will be capable of switching to a defined safe mode in the event of a detected anomaly. The spacecraft will also monitor the instrument and will switch the instrument to a pre-defined safe mode in the event of a detected anomaly in the DPU operation.
- Nominal ground contact will be for 3 out of every 24 hours.
- During ground contact all data will be transferred from the satellite solid state recorders to the ground station and the commands for the next 24 hours of operations will be uplinked.

2.2.2 Observing Mode Scenario

Figure 2.1 shows the assumed model for the definition of the SPIRE observations and the method by which the astronomer inputs his/her observing programme. The elements of the model are summarised below.

- **AOT (Astronomical Observation Template):** The observer is given a choice of observation types that can be carried out by the instrument and telescope. He/she is given a template to fill in with the details of the sources to be observed and the parameters for the particular observation. At this stage the parameters (User Parameters) are in astronomical terms – source name; RA, DEC; signal-to-noise; area to be mapped; spectral range and resolution etc.

- **Astronomical Observation Request (AOR)**: The Herschel Science Centre (HSC) takes the inputs from the astronomer via the Herschel Proposal Handling System and is responsible for their conversion into **Observatory Functions** with parameters for the **Spacecraft Functions**, **Instrument Functions** and **Instrument Data Configurations** that make up the Observatory Function.

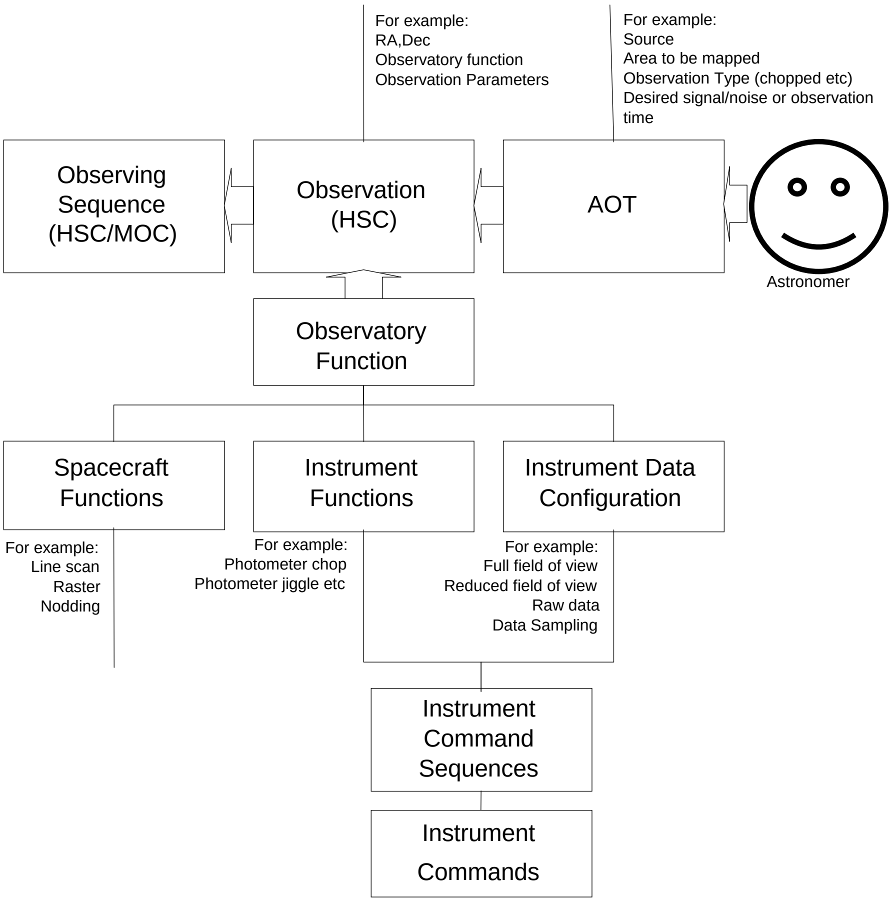


Figure 2.1: Diagrammatic representation of the connection between the various elements for the implementation of the SPIRE Observe Mode.

- **Observing Sequence:** The Observations required for a particular programme are put together into an Observing Sequence to be implemented by the MOC. The scheduling of the Observing Sequence is defined by the HSC and implemented by the MOC.
- **Observatory Function:** A combination of Spacecraft and Instrument Functions and Data Configurations which, with the appropriate input parameters, allow an Observation to be carried out.
- **Spacecraft Functions:** These are the operations that can be carried by the spacecraft to point the telescope such as line scan; raster; staring etc They are fully described in AD1 – for information they are summarised in Section 2.4. Spacecraft functions also include operations by the spacecraft on-board data handling sub-system (CDMS) to switch power to the instrument; send commands; collect data etc.
- **Instrument Functions:** These are the operations to be carried out with the instrument such as Photometer Chop, Photometer Jiggle, Spectrometer Scan, etc. Combined with the Spacecraft Functions, they fully define how an observation is to be carried out.
- **Instrument Data Configuration:** In addition to specifying how the instrument is to be operated for a given operation, the on-board data processing needs to be specified along with the data to be sampled and the manner in which the detector data is sampled. This will be done be choosing from a number of Data Configurations such as Photometer Full Field, Spectrometer Single Pixel, etc.

- **Instrument Command Sequences:** The instrument will be operated by building the high level instrument functions from a command language built up of Instrument Command Sequences . These are an intermediate set of logical instrument control functions such as Chop Start or Read Photometer Frame that allow the instrument controllers to build any required Instrument Function without resort to low level commands.

Instrument Commands: This is the low level command language used to control the instrument

2.3 Satellite operations

This section describes the operations assumed to be available from the satellite and required by the SPIRE instrument for the pointing of the telescope. Full details of the spacecraft capabilities are given in AD1. See Section 5 for more details on the implementation and the scientific merit of these operations.

2.3.1 Coordinate systems

The spacecraft and array coordinate system is as shown in Figure 2.2. The telescope boresight is the X direction, with the nominal Sun direction along the Z axis. The detector arrays are in the Y-Z plane, and are overlaid on the sky. The three arrays overlap on the sky, ideally with no misalignment. In practice there will be some misalignment: the centre of the PSW array is defined to be the (0,0) position. The chopping/nodding direction is along the Y-axis. For scanning observations, the telescope scan direction ϕ_{scan} is defined with respect to the +Y axis.

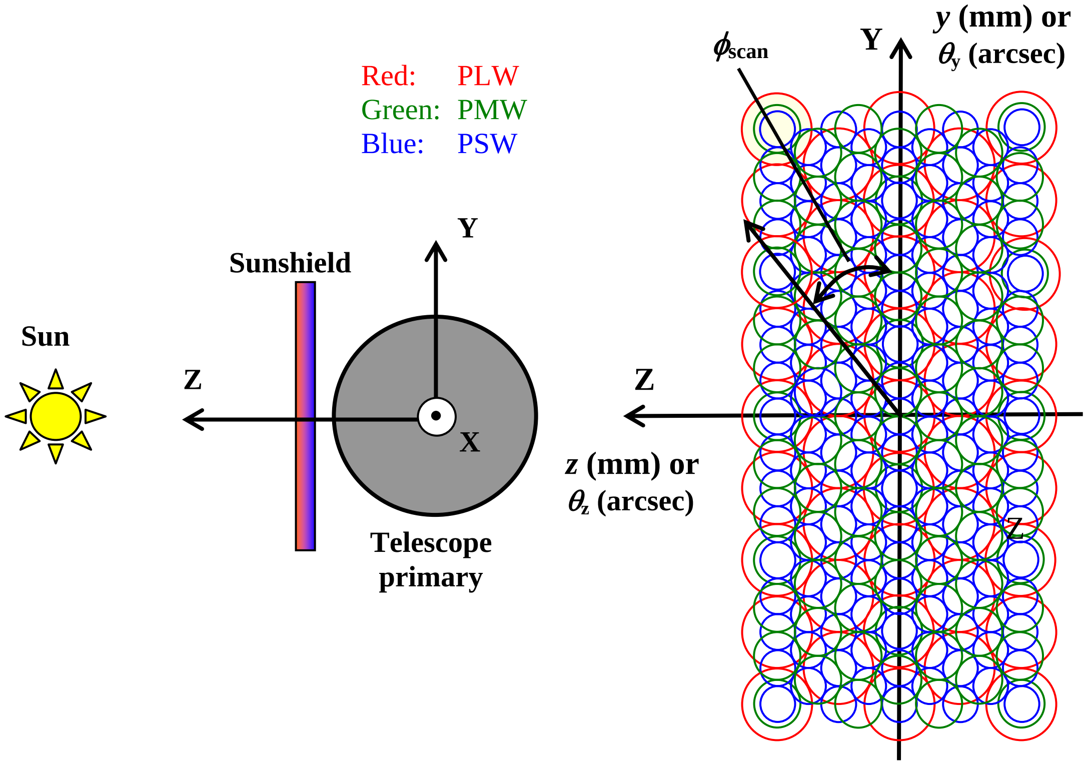


Figure 2.2: Coordinate system for satellite pointing and array orientation.

Coordinates in the Y-Z plane can be expressed in arcseconds on the sky or mm in the focal plane with angle on the sky related to distance in the focal plane related by the plate scale equation.

The rotation angle, of the spacecraft/array frame with respect to the RA-Dec frame is as defined by the angle α, between the RA and Z axes as shown in Figure 2.3.

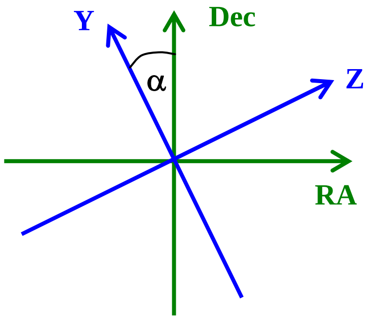


Figure 2.3: Definition of the rotation angle between the celestial and spacecraft coordinate frames. The angle α is equivalent to the angle East of North specified in HSpot for the chop avoidance angle.

2.3.2 Pointing

It is assumed that SPIRE pointing will be defined with respect to the telescope boresight by a number of offset positions. One for the centre of the photometer arrays and one for the centre of the spectrometer arrays are shown in Figure 2.4. The offset positions will be chosen to optimise individually the implementation of the various observing modes.

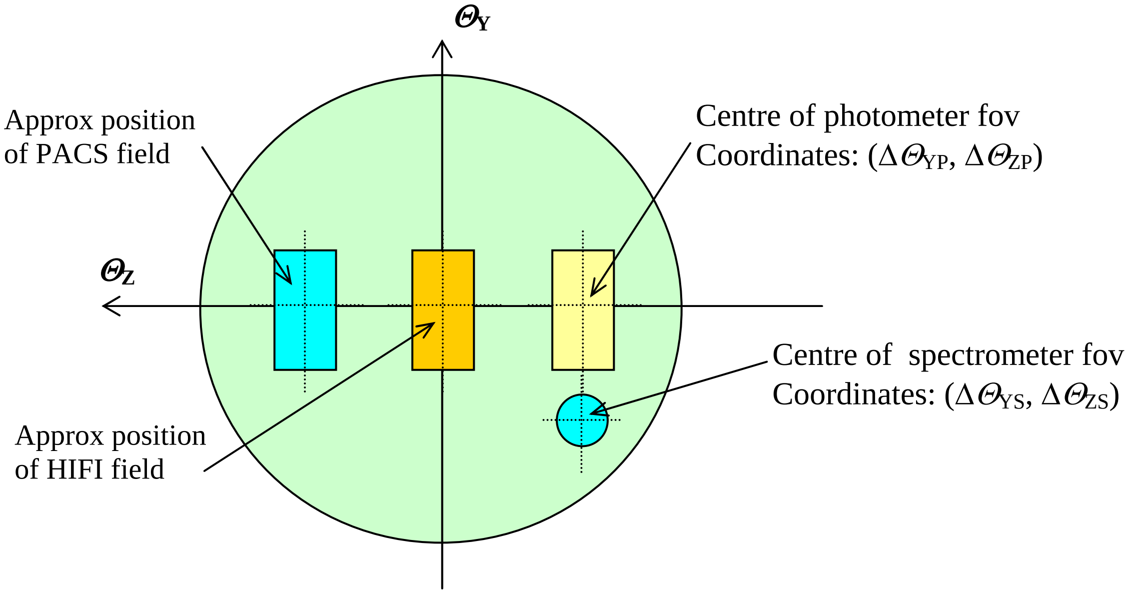


Figure 2.4: Definition of SPIRE pointing offsets with respect to the telescope boresight

When the telescope is pointed at a source at the request of SPIRE, it shall be aligned on one of the two positions defined. Any offsetting by the SPIRE BSM or the AOCS shall then be defined with respect to this position. The primary boresight position for the photometer shall be the central detector of the PSW array, and for the spectrometer, the primary boresight shall be the central detector of the SSW array. Other boresight positions (up to 76 in number) can be defined if necessary.

The telescope pointing capabilities are described in RD 3 and RD 4.

Comment: Sunil needs to check if this is fully consistent with other documents.

2.3.3 Pointing errors

The Herschel/Planck IID-A provides the following information on the telescope pointing accuracy:

Absolute Pointing Error (APE): The angular separation between the commanded direction and the instantaneous actual direction.

Pointing Drift Error (PDE): The angular separation between the short time average (barycentre of the actual pointing during some time interval) and a similar average pointing at a later time. The drift is given over 24 hours during the same observation period.

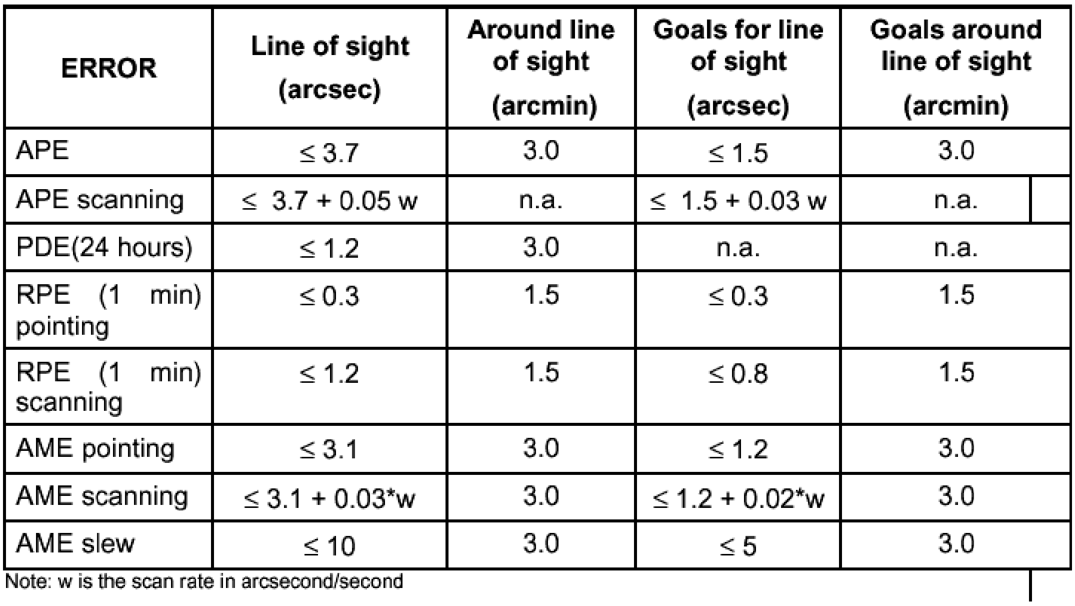
Relative Pointing Error (RPE): The angular separation between the instantaneous orientation of the satellite fixed axis at some time *t* and a reference axis (average, barycentre) over defined period. This is also known as the pointing stability.

Attitude Measurement Error (AME): The angular separation between the actual and the measured orientation of the satellite fixed axis defined instantaneously. This performance requirement is referred to as "a posteriori knowledge".

Absolute Rate Error (ARE) : The angular rate separation between the actual and the controlled angular rate about the satellite spin axis.

Spatial Relative Pointing Error (SRPE): The angular separation between the average orientation of the satellite fixed axis and a pointing reference axis which is defined relative to an initial reference direction.

The pointing specifications are given in the following table from the IID-A (the figures are for a temporal probability level of 68% - i.e., the error will be within the specified value for more than 68% of the time.



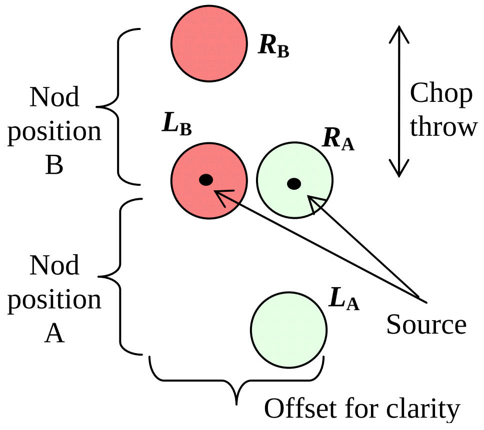
ERROR	Line of sight (arcsec)	Around line of sight (arcmin)	Goals for line of sight (arcsec)	Goals around line of sight (arcmin)
APE	≤ 3.7	3.0	≤ 1.5	3.0
APE scanning	≤ 3.7 + 0.05 w	n.a.	≤ 1.5 + 0.03 w	n.a.
PDE(24 hours)	≤ 1.2	3.0	n.a.	n.a.
RPE (1 min) pointing	≤ 0.3	1.5	≤ 0.3	1.5
RPE (1 min) scanning	≤ 1.2	1.5	≤ 0.8	1.5
AME pointing	≤ 3.1	3.0	≤ 1.2	3.0
AME scanning	≤ 3.1 + 0.03*w	3.0	≤ 1.2 + 0.02*w	3.0
AME slew	≤ 10	3.0	≤ 5	3.0

Note: w is the scan rate in arcsecond/second

Table 2.1: Herschel spacecraft pointing errors (from IID-A – the in-flight performance is expected to be close to the goal values).

2.3.4 Nodding

The NOD function of the telescope is an operation in which the target source is periodically moved from one instrument chop position to the other chop position by re-pointing the satellite, as shown in Figure 2.5. For a given detector, chopping the BSM creates two beams, designated left (L) and right (R). In Nod position A, the source is placed in beam R, and in nod position B it is placed in beam L . Due to thermal emission from the telescope and the ambient surroundings, each beam will have an offset signal, O_L or O_R, which are slightly different for the two beams due to inevitable slight asymmetries in the optical system and the background thermal radiation field. Furthermore, these offsets can be a function of time if, for instance, due to temperature drifts which might change the two offsets in a different way. The purpose of nodding is to subtract out these offsets, and to do so on a timescale faster than any such drifts.



Let S be the signal from the source.

Signal for Nod position A $= (R_A - L_A) = [(S + O_R) - O_L]$

Signal for Nod position B $= (R_B - L_B) = [O_R - (S + O_L)]$

Difference signal $= [(S + O_R) - O_L] - [O_R - (S + O_L)]$

$= 2S$

Figure 2.5: Nodding and corresponding removal of signal offsets.

A nod cycle comprises two nod positions (AB or BA).

2.3.5 Raster

The RASTER Spacecraft Function is a series of fine pointing operations of separated by slews such that the pointing of the telescope axis moves in a raster pattern. Figure 2.6 shows how the raster pattern will be constructed.

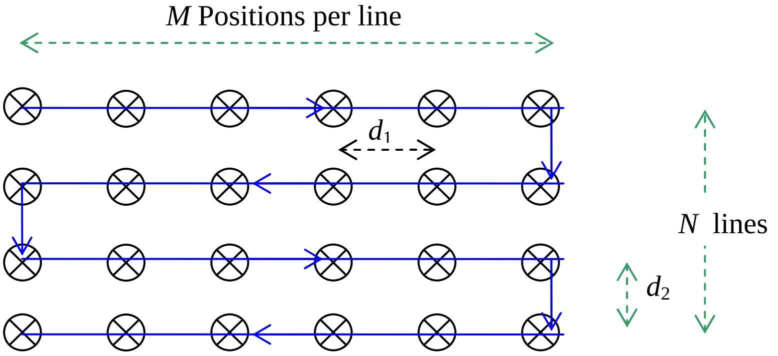


Figure 2.6: Pointing positions for a telescope RASTER function. The observation is specified in terms of M pointings per line separated by d_1 by N lines separated by d_2 arcsec.

2.3.6 Custom Map Pointing

For certain observations (FTS mapping in the case of SPIRE) a raster can be implemented as a set of specific pointings with arbitrary Y and Z positions. This mode is used to achieve full sampling in the most effective way for the FTS (see RD 5 for details).

2.3.7 Line Scan

In the LINE SCAN Spacecraft Function the satellite is slewed at a constant angular velocity along short parallel lines on the sky. Figure 2.7 shows how the operation is carried out. In NORMAL LINE SCAN

MODE, the sequence of individual lines is executed as shown. If required, a LINE SCAN WITH OFF-POSITION can be carried out. Here a fixed OFF position (referred to the map centre) can be visited periodically after a specified number of lines before carrying on with the line scan map. The maximum allowed scan length is 20^o for normal line scanning and 2^o for line scanning with OFF position.

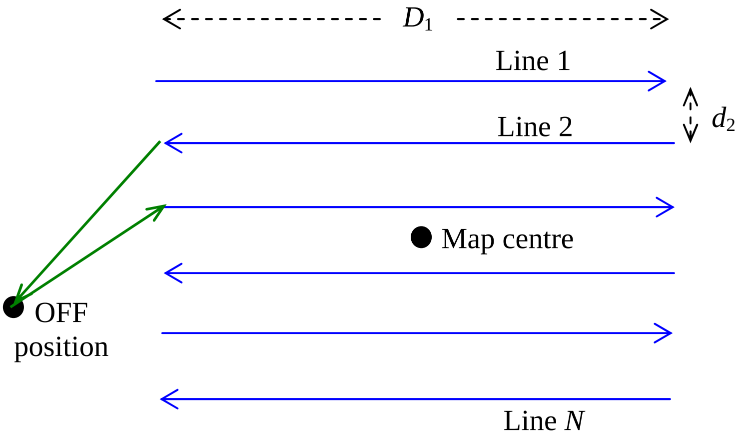


Figure 2.7: Telescope motions in carrying out a LINE SCAN observation of N lines, with line length D_1, line separation d_2, and the possibility of visiting a fixed OFF position periodically.

The detailed implementation of the SPIRE scan-map mode is described in RD 6 and RD 7.

During SPIRE observations, the photometer calibration source, PCAL, will be operated at intervals (typically once per hour) to track any responsivity drifts. To ensure that response to the modulated astronomical sky is not confused with response to PCAL, the BSM and telescope positions must be held steady while PCAL is being modulated. We assume an average slew time of three minutes, so the on-source integration time should be comparable or greater than this value to avoid highly inefficient use of time. For lengthy observations, such as scans or rasters taking an hour or more, times are defined during the observation (e.g., at the end of the telescope dwell time on a particular raster point, or at the end of a scan line) when PCAL operations will be carried out.

2.4 Chopping, nodding, rastering, and scanning parameters and overheads

The telescope and BSM motions involved in the various observing modes (chopping, nodding, scanning, rastering) are described in the *Herschel Pointing Modes* document and in the OMD. Further information is given here on how the times needed for different operations are defined or calculated. In this document, various formulas are used for calculating the telescope motion overheads. Note that the information in Sections 2.4.1 – 2.4.6 is now largely superseded by the HSpot tool, which calculates and tabulates the observatory overheads for a given AOR. These sections are retained in this document to provide an explanation of the origin of some of these overheads, and are therefore to be regarded as indicative only.

2.4.1 Telescope movement times

Slewing: A standard “tax” of 3-minutes is normally applied to all Herschel source acquisitions to represent a typical slewing time. It is therefore appropriate that the actual observation duration be at least of the same order to avoid highly inefficient operation of the observatory.

Re-pointing during an observation: The IID-A Section 5.12 specifies the requirement and goal for small slews executed during observations. The movement time, Δt_{motion}, is defined as the time between the start of the motion and the instant at which the new telescope position is deemed to have been reached, and depends on the angular distance moved, $\Delta\theta$, according to the following formula:

$$\Delta t_{\text{motion}} = 10 + (2\Delta\theta)^{1/2} \quad \text{(req.)} \qquad \Delta t_{\text{motion}} = 5 + (\Delta\theta)^{1/2} \quad \text{(goal)} \qquad (1)$$

where $\Delta\theta$ is in arcseconds.

Accelerating and decelerating: In establishing the desired scan speed for continuous scanning mode, the spacecraft scan acceleration will be fixed at a value

$$\ddot{\theta} = 0.05 \quad \text{arcmin s}^{-2} \qquad (2)$$

To attain a scan rate of $\dot{\theta}$ arcmin s^{-1} takes $\dot{\theta}/\ddot{\theta}$ seconds $0.5\dot{\theta}^2/\ddot{\theta}$ arcminutes. For example, the maximum scan rate of 1 arcmin s^{-1} requires 20 seconds and 10 arcmin.

2.4.2 Chopping

Chopping motions are illustrated in Figure 2.8. Chopping, through an angle $\Delta\theta_{\text{chop}}$ is normally along the Y-axis, and normally symmetrical about (0,0). The left beam is defined as the one on or towards the negative side of the Y-axis and the right beam as the one on or towards the positive side.

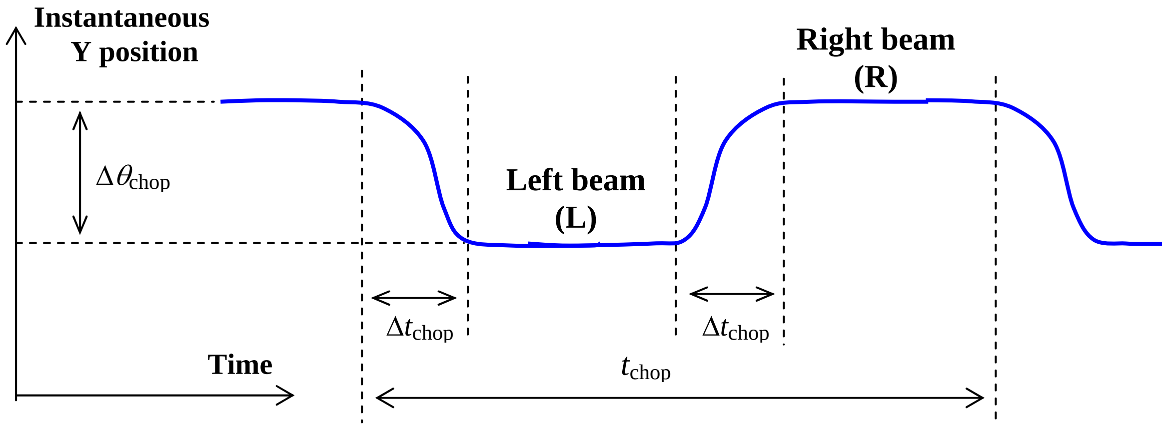


Figure 2.8: Definition of chopping parameters.

The time for one complete chop cycle is t_{chop}. Δt_{chop} is the time between the start of chop position motion and the instant at which data are deemed valid (BSM sky position within 1” of the required position). The nominal. The total “dead time” for one chop cycle is thus $2\Delta t_{\text{chop}}$. The nominal value of Δt_{chop} is 20 ms (BSM SSSD).

2.4.3 Jiggling

A jiggle cycle involves N_{jigpos} BSM positions. The sequence of motions is shown in Figure 2.9. The number of chop cycles carried out at each jiggle position is N_{chop}. The time taken to move from one jiggle position to another is Δt_{jig}. The chopping motion is interrupted for a time Δt_{jig} while the jiggle axis moves to an new position, and then chopping is resumed. The nominal value of Δt_{jig} is 100 ms (BSM SSSD).

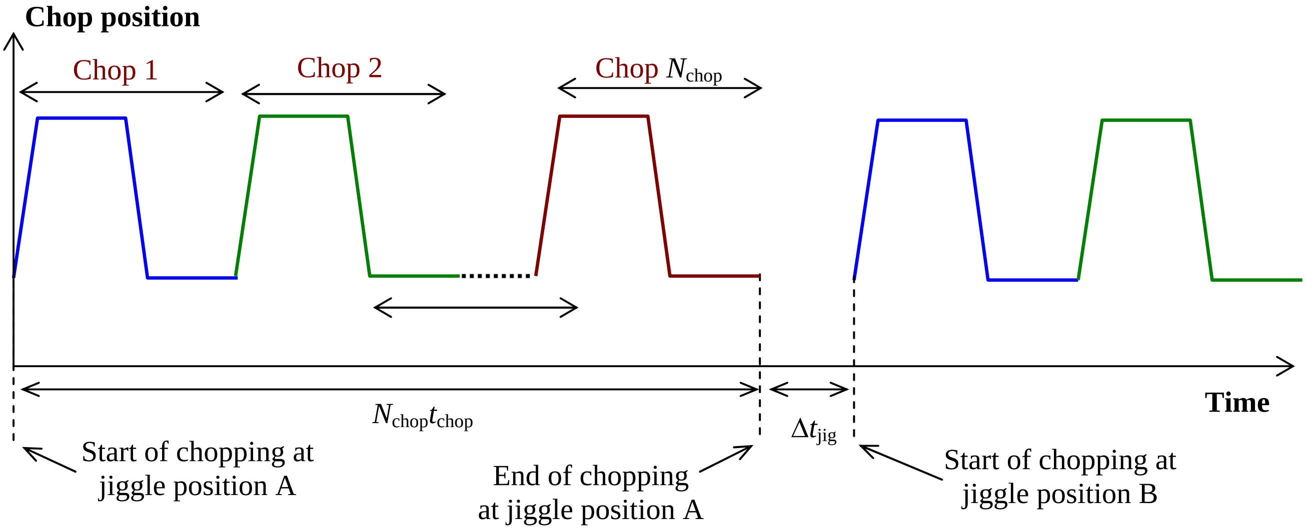


Figure 2.9: Timing of chop and jiggle movements.

The total time taken for a complete jiggle cycle of N_{jigpos} positions, involving N_{jigpos} - 1 jiggle position movements is

$$t_{jigcyc} = N_{jigpos}\left(N_{chop}t_{chop}\right) + \left(N_{jigpos} - 1\right)\left(\Delta t_{jig}\right) \qquad (3)$$

Note that in the case of chopping without jiggling, t_{jigcyc} reduces to $N_{chop}t_{chop}$.

The number of jiggle cycles in an observatrion is denoted N_{jigcyc}.

2.4.4 Nodding

Chopping motions are illustrated in Figure 2.10. The nodding movement time, Δt_{nod}, is defined as the time between the start of nod motion and the instant at which the new telescope position is deemed to have been reached (assumed to be the same for both nod directions). Δt_{nod} is given by Equation (1).

$$\Delta t_{nod} = 10 + \left(2\Delta\theta_{chop}\right)^{1/2} \quad \text{(req.)} \qquad \Delta t_{nod} = 5 + \left(\Delta\theta_{chop}\right)^{1/2} \quad \text{(goal).} \qquad (4)$$

For example, with θ_{chop} = 126 arcseconds, the nod time is 25 sec. (req.) or 16 sec. (goal).

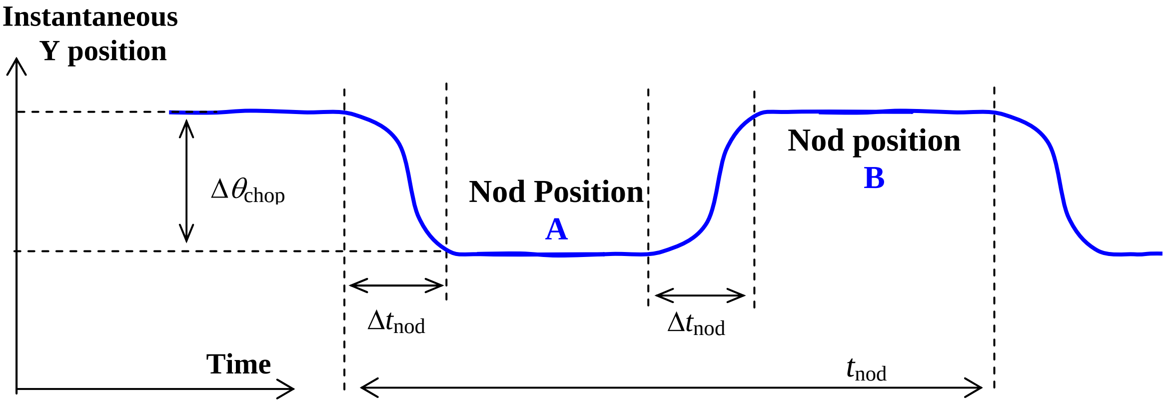


Figure 2.10: Definition of nodding parameters.

For the case of chopping without jiggling, the total time per nod cycle, t_{nod}, is

$$t_{\mathrm{nod}} = 2\left(N_{\mathrm{chop}} t_{\mathrm{chop}} + \Delta t_{\mathrm{nod}}\right) . \qquad (5)$$

When jiggling is being carried out, the total time for a complete nod cycle involving N_{jigcyc} jiggle cycles per nod cycle is

$$t_{\mathrm{nod}} = 2\left(N_{jigcyc} t_{jigcyc} + \Delta t_{\mathrm{nod}}\right) . \qquad (6)$$

The total number of nod cycles (AB or BA) to be carried out in an observation is N_{nod}.

2.4.5 Rastering

A standard raster observation consists of N lines with M raster points per line. The raster movement times, Δt_{step} for repointing by angle d_1 along a line, or Δt_{line} for repointing by angle d_2 between lines, are also given by equation (1). For a raster of 4 x 4 arcminute jiggle maps, the step could be 3.5 arcmin (to provide some overlap between the sub-maps). The step time for each movement of the raster pattern is then ~ 30 sec. (reg.) or ~ 20 sec. (req.).

The total time spent in moving the telescope between raster positions is

$$\Delta t_{\mathrm{rast}} = (M-1)\Delta t_{step} + (N-1)\Delta t_{line} . \qquad (7)$$

2.4.6 Scanning

A standard scanning observation consists of N scans, each of length D_1 with spacing d_2. A line scan is not deemed to have started until the telescope has attained the required scan speed, $\dot{\theta}_{\mathrm{line}}$. The telescope turn around time at the end of each line is Δt_{turn}, defined as the time between the end of one line scan and the start of the next. To arrive at an estimate of the turn-around time, we can assume that the additional time needed to execute the pointing shift between lines is negligible and that the acceleration and deceleration times are the same, giving

$$\Delta t_{turn} = 2\dot{\theta}_{\mathrm{line}} / \ddot{\theta} . \qquad (8)$$

The total time for a scan map observation is

$$t_{\mathrm{scan}} = N\left(\dot{\theta}_{\mathrm{line}} D_1 + \Delta t_{\mathrm{turn}}\right) \qquad (9)$$

where we also assume that a time $\Delta t_{\mathrm{turn}}/2$ is needed both for the first acceleration at the start, and the last deceleration at the end of the observation.

Scanning can be implemented with or without chopping. In the former case, the chopper is assumed to be free running during the whole of the observation with a chop period much shorter than the time per scan, so that the total time does not depend on the chop period.

3. OBSERVATORY FUNCTIONS

In this section the OBSERVATORY and INSTRUMENT FUNCTIONS outlined in Section 2 are discussed in more detail, including the scientific reasoning behind the choice of a particular OBSERVATORY FUNCTION. Also given in this section are details of the required INSTRUMENT DATA CONFIGURATIONS and the INSTRUMENT COMMAND SEQUENCES required to build the nominal set of INSTRUMENT FUNCTIONS.

3.1 Observatory Functions for the Photometer

Any astronomical observations with the photometer can be implemented with one of three types of OBSERVATION. These are all available as options within one photometer AOT defined to assist astronomers in preparing the input necessary to specify the OBSERVATIONS.

The OBSERVATORY FUNCTIONS for the photometer are listed below

OBSERVATION	**OBSERVATORY FUNCTION**	**Name**	**Comments**
Point source photometry	POF 1	Chop without jiggling	Accurate pointing and source position (not baseline)
	POF 2	Seven-point jiggle map	Inaccurate pointing or source position (baseline)
Jiggle mapping	POF 3	*n*-point jiggle map	Field mapping (baseline)
	POF 4	Raster map	Extended field mapping (not baseline – scan map to be adopted)
Scan mapping	POF 5	Scan map without chopping	Large-area mapping (baseline for area greater than one jiggle-map field)
	POF 6	Scan map with chopping	Large area mapping (with 1/*f* noise) (not baseline)
Peak-up	POF 7	Photometer peak-up	Determination of pointing offsets (not baseline)
Calibrate	POF 8	Photometer calibrate	Responsivity tracking (not baseline but may be introduced if deemed optimal)
Parallel		SPIRE-PACS Parallel Mode	For large-area scan maps only
Serendipity		Serendipity	Data will be taken but no ICC provision for processing
Engineering modes		Special engineering/ commissioning modes (TBD)	TBD

Table 3.1: Photometer Observatory Functions.

3.1.1 POF 1: Chop Without Jiggling

Purpose: This is similar to what is often done on ground-based submillimetre telescopes. It is designed to make observations of a point or compact source of accurately known position. In the case of SPIRE, chopping between pairs of pixels gives maximum sensitivity because in that case the source is being observed all the time. There is simultaneous overlap at all three wavelengths for several sets of detectors on the SPIRE arrays. The optimum sets to use for chopped photometry are sets 1 and 2 in Figure 3.1 as this minimises the BSM power dissipation by chopping symmetrically about the rest position with the smallest possible angular deviation. Sets 2 and 3, or their equivalents on the opposite side are also usable but with higher BSM dissipation.

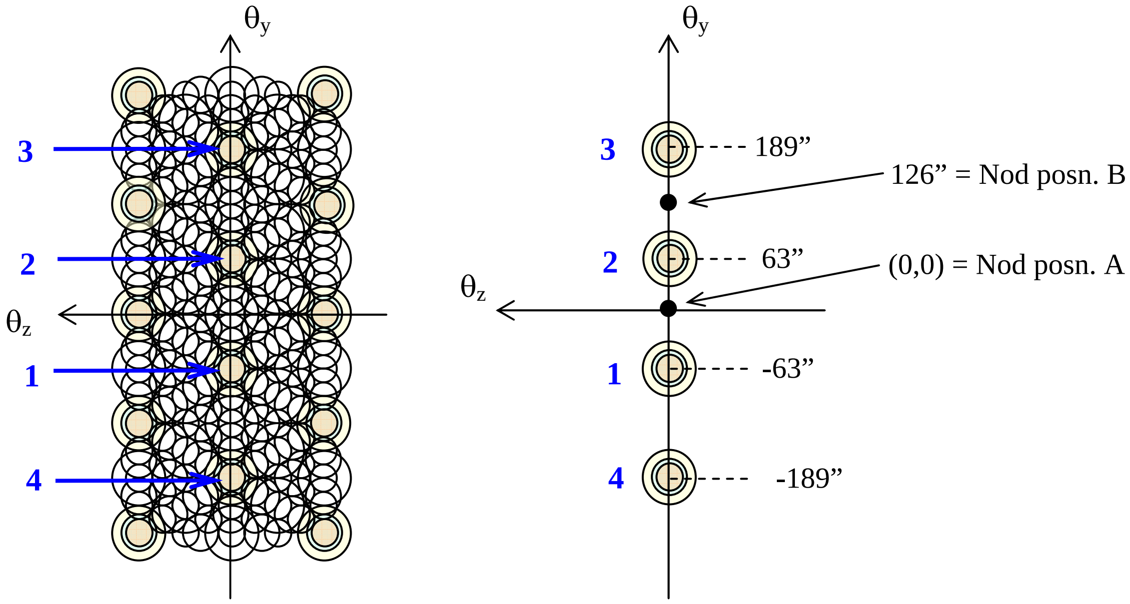


Figure 3.1: Left: sets of detectors (shaded) for which there is simultaneous overlap in all three bands for the feedhorn array option. Right: the sets of overlapping detectors on the Y axis shown separately with their angular distance from the boresight as indicated.

Description:

1. This Observatory Function is composed of the following instrument and Spacecraft Functions:

Instrument Function:	Photometer Chop
Spacecraft Function:	Nod

2. Chop distance on the array: This is determined by the horn centre-centre spacing, and is equal to twice the 5-mm outside diameter of the PLW horn. The chop angle on the sky is equal to the distance moved in the focal plane multiplied by the plate scale (12.6 “/mm):

Chop distance in the array focal plane: $\Delta y_{chop} = 2 \times 5 \text{ mm} = 10 \text{ mm}$
Chop angle on the sky: $\Delta\theta_{chop} = (10 \text{ mm})(12.6 \text{ "/mm}) = 126 \text{ arcsec.}$

This mode requires pointing accuracy sufficiently good that the loss of signal due to the pointing error is acceptable. The signal loss factors for the photometer beams are shown in Figure 3.2 The required APE (3.7") corresponds to (11%, 6%, 3%) signal loss in the PLW, PMW and PSW bands mm respectively. The goal (1.5") corresponds to (2%, 1%, 0.5%) signal loss. For most observations, 11% is not acceptable, but 2% is. Therefore, the required APE is not good enough to allow accurate photometry at 250 mm without peaking up, but the goal is sufficient to allow this. In the event that the pointing accuracy is not good enough to allow blind pointing then either:

(i) this Observatory Function will not be used, with POF 2 used instead (note that this is foreseen to be the default mode);
(ii) it will be used but only when preceded by a peaking-up routine (POF 7) - currently not the not default, and viability TBC.

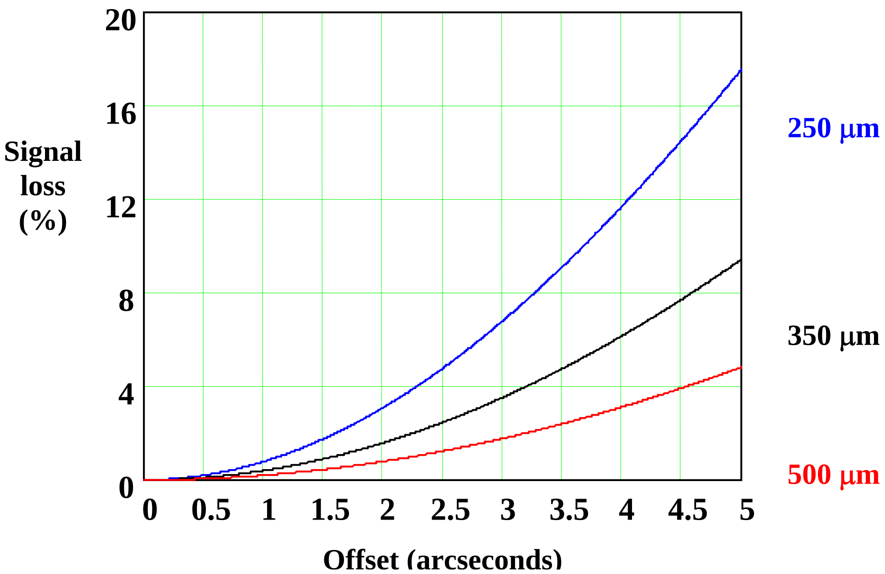


Figure 3.2: Signal loss in the three SPIRE bands vs. pointing accuracy for a point source.

3. In nominal operation, the BSM chops symmetrically in the Y-direction at f_{chop} (= $1/t_{chop}$) about its rest position, moving the source alternately onto two sets of three co-aligned detectors near the centre of the arrays.

4. Nodding is optional (the baseline is that it will be done). The number of chop cycles carried out at each nod position is N_{chop}.

5. Defining the two nod positions as A and B, the basic nodding sequence is AB BA . . . AB BA. To execute this, the required steps in a POF 1 observation with nodding are as follows:

(1) The telescope is pointed at the (0,0) position, corresponding to nod position A
(2) The BSM chops ± 63” about its rest position, between detector set 1 and 2 for time t_{dwell}.A
(3) The telescope is moved to nod position B (126”, 0)
(4) The BSM chops ± 63” about its rest position, between detector set 2 and 3 for time t_{dwell}.B
(5) The BSM chops ± 63” about its rest position, between detector set 2 and 3 for time t_{dwell}.B
(6) The telescope is nodded back to position (0, 0)
(7) The BSM chops ± 63” about its rest position, between detector set 1 and 2 for time t_{dwell}.A
(8) The BSM chops ± 63” about its rest position, between detector set 1 and 2 for time t_{dwell}.A
(9) The telescope is moved back to nod position B (126”, 0)
(10) The BSM chops ± 63” about its rest position, between detector set 2 and 3 for time t_{dwell}.B

etc. for as long as is required.

Here t_{dwell} is defined as the time between telescope arriving (with stable pointing) at a position and it being commanded to move to next position.

Depending on the number of nod cycles (N_{nod}) required, the sequence could be ended after step 4 ($N_{nod} = 1$: AB), step 7 ($N_{nod} = 2$: AB BA), step 10 ($N_{nod} = 3$: AB BA AB), etc.

The baseline implementation is ABBA as the basic cycle, with the number of repetitions defined as the number of such cycles (so $N_{nod} = 2$ for 1 repetition, 4 for two repetitions etc.)

6. An overall improvement in S/N by a factor of 1.22 can be achieved via on-array chopping and nodding, as derived in
7. A dwell time between nods of > 1 minute and < 4 minutes is appropriate, otherwise the telescope settling time overhead (up to ~30 seconds) will become prohibitive or the interval between nods may become excessive, either requiring an excessively long observation or making the data susceptible to offset drifts.
8. Although only the primary set of detectors are essential for this observing mode, the other detectors in the arrays will also be sampled, providing a sparsely sample map of the region around the source.
9. The detectors will be sampled synchronously with the BSM movements at a nominal rate close to 16 Hz (the exact value depends on the adopted bias frequency).

Instrument and Spacecraft Functions used and their parameters: See Table 3.2.

Instrument Function: Photometer Chop				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chop frequency (f_{chop})	0.2 - 2 Hz	2 Hz in Y	
2	Chop direction	Any direction in the Y-Z plane	Parallel to the Y-axis	
3	Chop throw ($\Delta\theta_{chop}$)	Any value within the BSM range (± 130” in Y; ± 30” in Z)	126" (±63") on the sky parallel to Y-axis	126” provides detector-detector chopping
4	Number of chop cycles per nod position (N_{chop})	Min = 4 Max = None	128	
Spacecraft Function: Nod				
1	Nodding	ON or OFF	ON	Nodding is optional
2	Dwell time on each nod position (t_{dwell})	Min = 8 sec. Max = None	64 sec.	In the standard AB BA A . . sequence, the time spent in each nod position is thus $2t_{dwell}$ except for the first and the last positions.
3	Nod direction	Same as the chop direction	Parallel to the Y-axis	
4	Nod throw ($\Delta\theta_{chop}$)	Same as the chop throw	126"	
5	Total number of nod cycles (N_{nod})	Min = 1 Max = None	1 - 4	

Table 3.2: Spacecraft and Instrument Functions for POF 1.

Typical parameters: The on-source integration time should be comparable or greater than the typical slew time of ~ three minutes. The time needed to nod the telescope is ~ 20 s, and the time spent at each nod position should be at least several times this value to avoid high inefficiency.

As a standard set of parameters, we adopt a 2-Hz chop frequency with 128 chop cycles per nod position (i.e., 64 sec. dwell time per position). The times needed for observations with different numbers of nod cycles are given in
Table 3.3, where a nod time of 20 seconds is assumed.

Chop freq. (Hz)	$f$chop	2	Hz
Chop period (sec.)	$t$chop	0.5	sec.
No. chop cycles/nod position	Nchop	128	
Nod overhead (s)	$t$nod	20	sec.

No. of nod cycles	**Action**	**Time (s)**	**Total time (s)**	**Integration time (s)**	**Efficiency (%)**
	Dwell on Nod Pos A	64			
	Nod movement	20			
1	Dwell on Nod Pos B	64	148	128	86.5
	Dwell on Nod Pos B	64			
	Nod movement	20			
2	Dwell on Nod Pos A	64	296	256	86.5
	Dwell on Nod Pos A	64			
	Nod movement	20			
3	Dwell on Nod Pos B	64	444	384	86.5
	Dwell on Nod Pos B	64			
	Nod movement	20			
4	Dwell on Nod Pos A	64	592	512	86.5
	Dwell on Nod Pos A	64			
	Nod movement	20			
5	Dwell on Nod Pos B	64	740	640	86.5

Table 3.3: Standard parameters, integration times and achieved sensitivity for POF 1 observations.

3.1.2 POF 2: Seven-Point Jiggle Map

Purpose: This Observatory Function is designed for observation of an isolated compact source where uncertainties in the telescope pointing and/or the source coordinates mean that the accuracy of blind pointing cannot be relied upon. A small map must be made around the nominal pointing position to make sure that the source signal can be correctly estimated. It is effectively a combination of seven separate measurements using POF 1.

Description:

1. POF 2 is composed of the following instrument and Spacecraft Functions:

   Instrument Function: Photometer Chop
   Photometer 7-Point Jiggle
   Spacecraft Functions: Nod

2. The BSM is used to do a small 7-point hexagonal jiggle map with spacing $\Delta\theta_7$ arcsec., as shown in Figure 3.3. A suitable value for $\Delta\theta_7$ is ~ 6”: this spacing is 1/3 of the PSW beam (so consistent with full sampling), and is almost twice the APE.

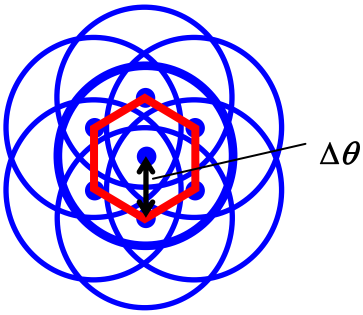


Figure 3.3: Seven-point hexagonal jiggle pattern. The central position is re-visited at the end to make for eight positions altogether.

3. From such a 7-point map, the total flux of the source can be computed.
4. At each position in the seven-point, the equivalent of a POF 1 observation (without nodding) is made.
5. Nodding is optional, with the baseline assumption that it will be necessary.
6. If nodding is being implemented, a complete 7-point is carried out in each nod position before the telescope is nodded to the other position.
7. As for POF 1. Although only the primary sets of detectors are essential for this mode, the other detectors in the arrays will also be sampled, providing a sparsely sample map of the region around the source.
8. The baseline implementation of POF2 in HSpot has ABBA as the basic cycle, with the number of repetitions defined as the number of such cycles (so N_{nod} = 2 for 1 repetition, 4 for two repetitions etc.)

On-board processing and data rate: As POF 1.

Instrument and Spacecraft Functions used and their parameters: See Table 3.4.

Instrument Function: Photometer Chop				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chop frequency (f_{chop})	As for POF 1	As for POF 1	
2	Chop direction	As for POF 1	As for POF 1	
3	Chop throw ($\Delta\theta_{chop}$)	As for POF 1	As for POF 1	
4	Number of chop cycles per nod position (N_{chop})	N/A	N/A	Not specified in this mode
Instrument Function: Photometer Jiggle				
1	Jiggle pattern offset of each of the six neighbour positions from the centre ($\Delta\theta_7$)	3 – 10 arcsec.	6 arcsec.	Eight positions are observed: centre + hexagon + centre again.
2	Number of chop cycles/ jiggle position (N_{chop})	Min = 2 Max = None	16	Nominal time spent in executing jiggle: 8x8=64 sec.
Spacecraft Function: Nod				
1	Nodding	As for POF 1	As for POF 1	
2	Dwell time on each nod position (t_{dwell})	As for POF 1, but BSM overheads may be different	As for POF 1, but BSM overheads may be different	
3	Nod direction	As for POF 1	As for POF 1	
4	Nod throw ($\Delta\theta_{chop}$)	As for POF 1	As for POF 1	
5	Total no. of nod cycles (N_{nod})	As for POF 1	As for POF 1	

Table 3.4: Spacecraft and Instrument Functions for POF 2.

Standard parameters: As a nominal case, we shall adopt f_{chop} = 2 Hz and 16 chop cycles per 7-point position. We then have 8 seconds per 7-point position and 64 seconds per nod position. The times needed for observations with different numbers of nod cycles are given in Table 3.5 below. As for POF 1, the last column lists the achieved rms flux density in the PLW band (the slowest, considering instrument sensitivity and typical source SED), assuming sensitivity as predicted in the *SPIRE Sensitivity Models* document.

Chop freq. (Hz)	*f* chop	2	Hz	
Chop period (sec.)	*t* chop	0.5	sec.	
No. chop cycles/jiggle position	*N* chop	16		
Jiggle settling time (s)	→*t* jig	0.01	sec.	(Note: could be effectively zero)
Nod overhead (s)	→*t* nod	20	sec.	

No. of nod cycles	Action	Jiggle Position	Time (s)	Total time (s)	Integration time (s)	Efficiency (%)
	Dwell on Nod Pos A	Centre	8.0			
		Offset 1	8.01			
		Offset 2	8.01			
		Offset 3	8.01			
		Offset 4	8.01			
		Offset 5	8.01			
		Offset 6	8.01			
		Centre	8.01			
			64.07			
	Nod movement		20			
1	Dwell on Nod Pos B	Repeat	64.07	148	128	86.5
	Dwell on Nod Pos B		64.07			
	Nod movement		20			
2	Dwell on Nod Pos A		64.07	296	256	86.5
	Dwell on Nod Pos A		64.07			
	Nod movement		20			
3	Dwell on Nod Pos B		64.07	444	384	86.5
	Dwell on Nod Pos B		64.07			
	Nod movement		20			
4	Dwell on Nod Pos A		64.07	593	513	86.5
	Dwell on Nod Pos A		64.07			
	Nod movement		20			
5	Dwell on Nod Pos B		64.07	741	641	86.5

Table 3.5: Standard parameters, integration times and achieved sensitivity for POF 2 observations. Note: for this mode the jiggle settling time can probably be taken as zero (movement of only about 6” compared to the nominal chop distance of 126”).

3.1.3 POF 3: *n*-Point Jiggle Map

Purpose: This mode is for mapping objects or regions which are extended with respect to the SPIRE beam but smaller than a few arcminutes in size. Its implementation is very similar to POF 2.

Description:

1. POF 3 is composed of the following instrument and Spacecraft Functions:

Instrument Function:	Photometer Chop Photometer *n*-Point Jiggle
Spacecraft Functions:	Nod

2. The BSM is used to make an *n*-point jiggle map while chopping with a throw greater than the size of the object to be mapped. The maximum throw is 4 arcminutes (± 2 arcminutes) as illustrated below.

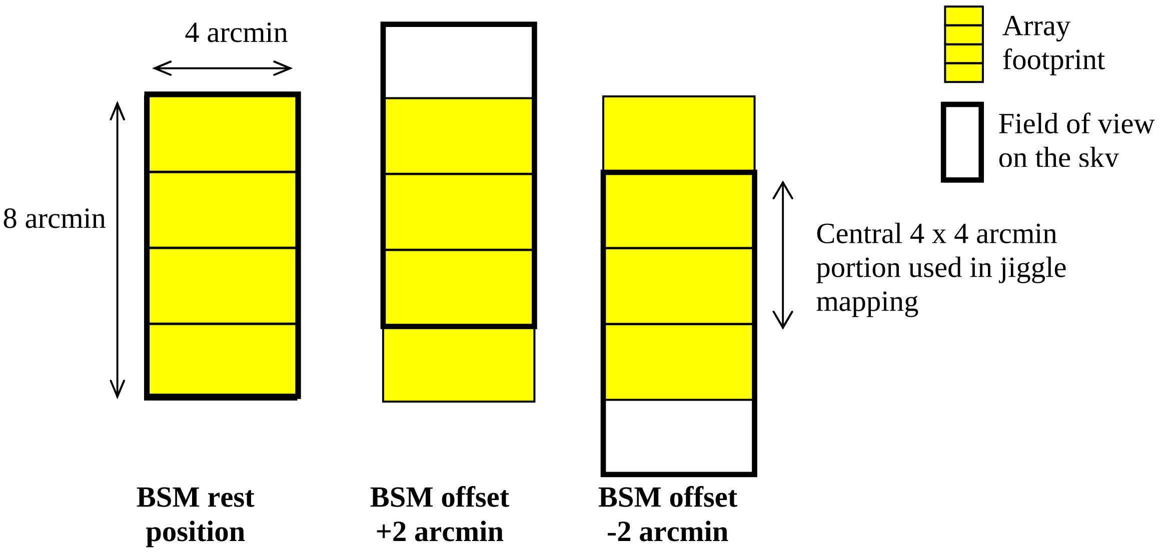


Figure 3.4: Jiggle mapping with the maximum chop throw of 4 arcminutes. The 4 x 8 arcminute field of view transmitted by the photometer optics is chopped by +/- 2 arcminutes as shown. The detectors in the central square 4 x 4 arcminute part of the array are alternately chopped from one side of the available field of view to the other. The detectors in the outer 2 x 4 arcminute portions at each end are chopped between the sky and the instrument cold box, producing no usable data.

3. For full sampling at all wavelengths, $n = 64$. Considering the simplified case of square-packed horns, the step size must be half of the smallest beam (PSW) = 9” and the number of steps must accommodate the need to cover the distance between beams for the PLW band = 72”. Eight steps in each orthogonal direction are thus required. The geometry of the juggle pattern is hexagonal for the hexagonally packed feedhorns, but the number of steps required is still 64.

4. Any value of *n*, with any allowed offset positions can be used. But in practice, suitable values of *n* would be 16, 32 and 64 with the appropriate symmetrical arrangement of offset positions. A value of 16 can provide a fully sampled map in the PLW band, and 32 is enough to provide full sampling in the PMW band, and 64 is needed for simultaneous full sampling in all bands.

5. The jiggle positions shall be defined by angles $\Delta\theta_Y$ and $\Delta\theta_Z$ in the Y and Z directions (with respect to the BSM rest position).

6. The sequence in which the jiggle positions are visited is TBD. The positions and the sequence will be standard for all jiggle-map observations.

7. The chop throw is chosen to be greater than the size of the field to be mapped (baseline is to use ± 2 arcminutes).

8. Nodding is optional (baseline is that it is done).

On-board processing and data rate: As for POF 1.

Instrument and Spacecraft Functions used and their parameters: See Table 3.6.

Instrument Function: Photometer Chop

No.	Parameter	Range of values	Nominal value	Comments
1	Chop frequency (f_{chop})	As for POF 1	As for POF 1	
2	Chop direction	As for POF 1	As for POF 1	
3	Chop throw ($\Delta\theta_{chop}$)	As for POF 1	± 2 arcminutes	
4	Number of chop cycles per nod position (N_{chop})	N/A	N/A	Not specified in this mode
Instrument Function: Photometer Jiggle				
1	Jiggle pattern	n-point with positions ($\Delta\theta_Y$,$\Delta\theta_Z$) with respect to the pointed position n = 16, 32, 64	n = 64	
2	Number of chop cycles/ jiggle position (N_{chop})	Min = 2 Max = none Multiples of 2	4	
3	Number of jiggle positions/nod position (N_{jigpos})	For n = 64: N_{jigpos} = 4, 8, 16, 32	16	With n = 64 and N_{jigpos} = 16, there are four nod cycles (AB BA AB BA) in the complete observation.
Spacecraft Function: Nod				
1	Nodding	As for POF 1	As for POF 1	
2	Dwell time on each nod position (t_{dwell})	Min = 32 sec. Max = none Multiples of 32	32	
3	Nod direction	As for POF 1	As for POF 1	
4	Nod throw ($\Delta\theta_{chop}$)	As for POF 1	± 2 arcminutes	
5	Total number of nod cycles (N_{nod})	As for POF 1	4 needed to get the basic observation (see Table 3.7)	

Table 3.6: Spacecraft and Instrument Functions for POF 3.

Standard parameters: The baseline adopted for a standard jiggle observation is as follows:

(i) there are 64 jiggle positions (n = 64);

(ii) the chop frequency is the standard value of 2 Hz;
(iii) the dead time due to the nodding motions is 20 seconds;
(iv) 16 jiggle positions will be done at each nod position;
(v) 4 chop cycles (2 seconds) per jiggle position.

The times needed for observations with different numbers of nod cycles are given in Table 3.7 below. We neglect BSM movement overheads in this tabulation.

Chop freq. (Hz)	2	Hz
No. of jiggle posns per nod posn	16	
Nod overhead (s)	20	sec.

No. chop cycles/jiggle position		4	8	12
Action	**Jiggle Position**	**Time (s)**	**Time (s)**	**Time (s)**
Dwell on Nod Pos A	1-16	32	64	96
Nod movement		20	20	20
Dwell on Nod Pos B	1-16	32	64	96
Dwell on Nod Pos B	17-32	32	64	96
Nod movement		20	20	20
Dwell on Nod Pos A	17-32	32	64	96
Dwell on Nod Pos A	33-48	32	64	96
Nod movement		20	20	20
Dwell on Nod Pos B	33-48	32	64	96
Dwell on Nod Pos B	49-64	32	64	96
Nod movement		20	20	20
Dwell on Nod Pos A	49-64	32	64	96
Total time (s)		336	592	848
Integration time (s)		256	512	768
Efficiency (%)		76.2	86.5	90.6

Table 3.7: Standard parameters, integration times and achieved sensitivity for POF 3 observations.

The sequence in which the 64 jiggle positions are visited is illustrated in Figure 3.5.

Note that in HSpot, the baseline adopted is four chop cycles per jiggle position, with one repetition involving 256 seconds on-source integration time. Longer integrations can be built up by increasing the number of repetitions.

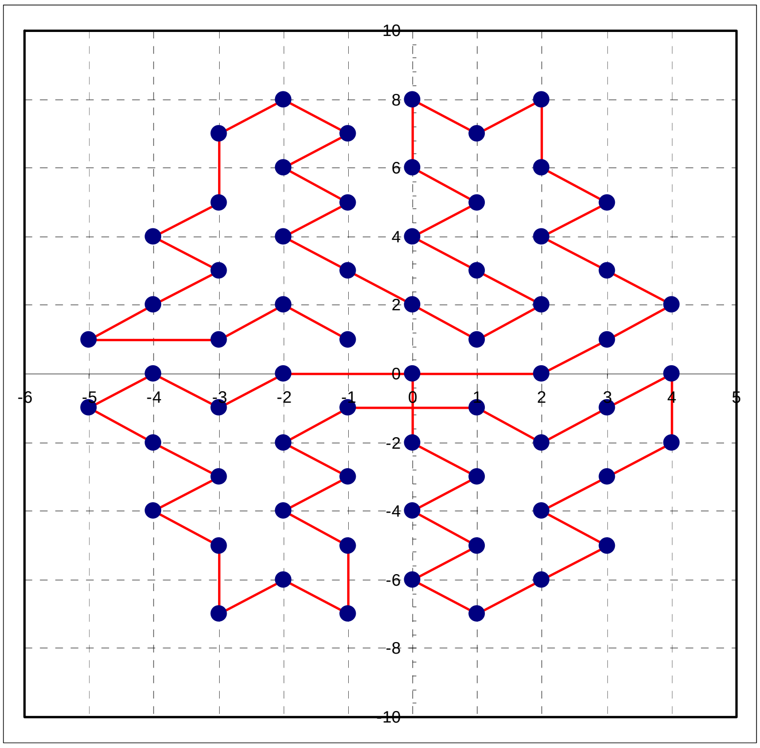


Figure 3.5: BSM positions for 64-point jiggle map. Sixteen positions are viewed in each of four nod cycles.

3.1.4 POF 4: Raster Map

Purpose: This Observatory Function is for mapping a region larger than the SPIRE field of view or to carry out a survey of a large area. However, scan-map is the nominal mode for large areas – the region size at which scan map will become the preferred mode is > 1 jiggle-map field, which means that POF 4 is not planned to be used. Nevertheless it is retained in case this policy changes as a result of evaluation of the in-flight performance of the system. POF 4 involves jiggle-mapping (POF 3) observations at a grid of telescope pointings. The telescope raster pointing capabilities are described in RD 3.

Description:

1. POF 4 is composed of the following instrument and Spacecraft Functions

Instrument Function:	Photometer Chop Photometer *n*-Point Jiggle
Spacecraft Functions:	Nod (optional) Normal Raster Pointing

2. The available field is the central 4 x 4 arcminute portion of the array.

3. The raster is a rectangular grid of separate pointings as shown in Section 2. The sequence at each point in the raster is exactly as in *n*-point Jiggle Map (POF 3).

4. The astronomer will wish to specify a region to be mapped in RA and Dec. The relationship between the coordinate frames will depend on exactly when the observations are scheduled - this issue must be addressed in the mission planning.

5. For long rasters, it will be necessary to interleave calibration (PCAL) operations.

On-board processing and data rate: As for POF 1.

Instrument and Spacecraft Functions used and their parameters: See Table 3.8 below.

Instrument Function: Photometer Chop				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chop frequency (f_{chop})	As for POF 1	As for POF 1	
2	Chop direction	As for POF 1	As for POF 1	
3	Chop throw ($\Delta\theta_{chop}$)	As for POF 1	As for POF 1	
4	Number of chop cycles per nod position (N_{chop})	N/A	N/A	Not specified in this mode
Instrument Function: Photometer Jiggle				
1	Jiggle pattern	As for POF 3	As for POF 3	
2	Number of chop cycles/ jiggle position (N_{chop})	As for POF 3	As for POF 3	
3	Number of jiggle positions/nod position (N_{jigpos})	As for POF 3	As for POF 3	
Spacecraft Function: Nod				
1	Nodding	As for POF 1	As for POF 1	
2	Dwell time on each nod position (t_{dwell})	As for POF 3	As for POF 3	
3	Nod direction	As for POF 1	As for POF 1	
4	Nod throw ($\Delta\theta_{chop}$)	As for POF 1	As for POF 1	
5	Total number of nod cycles (N_{nod})	As for POF 1	As for POF 1	
Spacecraft Function: Normal Raster Pointing				
1	Number of pointings per line (M)	Min = 2 Max = 32		Depends on size of region to be mapped
2	Number of lines (N)	Min = 1 Max = 32		Depends on size of region to be mapped
3	Angular distance between successive steps (d_1)	Min = 2 arcsec. Max = 3 arcmin.	Probably in the range 1 - 3 arcmin.	Some overlap between successive sub-maps is desirable
4	Angular distance between successive lines (d_2)	Min = 0 Max = 3 arcmin.	Probably in the range 1 - 3 arcmin.	Some overlap between successive sub-maps is essential

Table 3.8: Spacecraft and Instrument Functions for POF 4.

3.1.5 POF 5: Scan Map Without Chopping

Purpose: This Observatory Function is for mapping a large region of sky by scanning the telescope to provide spatial modulation of the signal. This is the baseline observing mode for most extragalactic and galactic surveys. Chopping is not done to avoid increasing confusion noise. The telescope scanning capabilities are described in RD 3.

Description:

1. POF 5 is composed of the following instrument and Spacecraft Functions

Instrument Function:	No-Chop
Spacecraft Functions:	Normal Line Scanning

2. The line scans are carried out along parallel lines as described in Section 2.
3. Chopping and nodding are not performed.
4. The telescope is scanned continuously across the sky. The spacecraft can scan at rates between 0.1 arcsec./sec and 1 arcmin./sec. (RD 3).
5. The scan direction must be specified in spacecraft coordinates.
6. For good sky sampling and uniformity of integration time over the map, particular scan angles are needed (RD 7).
7. The length of each line should be such that the turn-around time of the telescope (tens of seconds) does not constitute a large overhead. Short scans are less efficient.
8. The optimum scanning strategy for this mode is addressed in **Error! Reference source not found.** and involves cross-scanning in two directions to provide the necessary cross-linking for map-making.

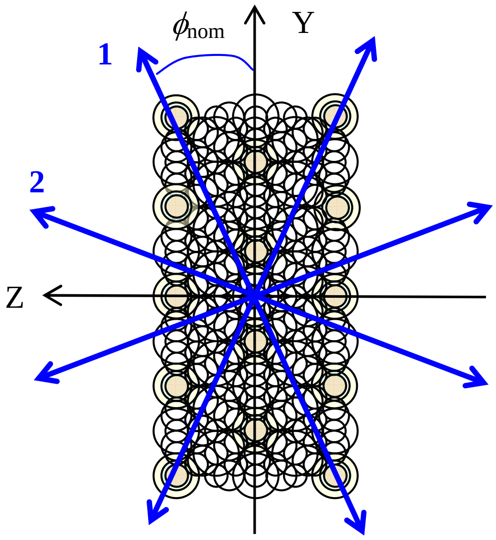


Figure 3.6: Allowed scan directions.

Detector sampling: The nominal rate for sampling of the demodulated detector signals is 16 Hz. The detectors will be sampled throughout the observation, including during the telescope turn-around periods. The usability of the data from turn-around periods is TBC – it will depend on the accuracy of the pointing information during acceleration and deceleration, and on the 1/*f* characteristics of the system. The (pessimistic) default assumption is that these data are not usable, and that the entire region requested to be observed is covered at the nominal scan rate.

On-board processing and data rate: The timing of the samples does not need to be synchronised to the telescope movements, but must be available on the ground in order to reconstruct the pointing and generate the maps. This will allow a specific telescope position to be assigned to every detector sample.

Instrument and Spacecraft Functions used and their parameters: See Table 3.9 below.

Instrument Function: Photometer Non-Chop				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chopping	OFF	OFF	BSM is held at fixed position.
Spacecraft Function: Line Scanning				
1	Scan mode	Normal line scan	Normal	
2	Scan direction (ϕ_{scan})	Arbitrary	Nominal values are defined in RD 7	
3	Scan rate ($\dot{\theta}$)	Min = 0.1" /sec. Max = 60"/sec.	30"/sec. or 60"/sec.	Depends on 1/f noise of the whole system
4	Angular length of each line scan (D_1)	Min = 4 arcmin. Max = 20°	Depends on observation.	Depends on size of area to be mapped. Unlikely to be > a few degrees.
5	Number of lines (N)	Min = 1 Max = 32		Depends on size of region to be mapped
6	Angular distance between successive lines (d_2)	Min = 0 Max. = TBD	See SPIRE OM	Depends on the array orientation wrt the scan direction. Some overlap between successive sub-maps is essential.

Table 3.9: Spacecraft and Instrument Functions for POF 5.

3.1.6 POF 6: Scan Map With Chopping

Purpose: This Observatory Function allows for mapping a large region of sky by scanning the telescope with the chopper operating. This mode could be useful in the event of high 1/f noise degrading the S/N for non-chopped scan observations. It is not planned to implement it unless there are problems with the operation or data quality when using POF 5.

Description:

1. POF 6 is composed of the following instrument and Spacecraft Functions

Instrument Function:	Photometer Chop
Spacecraft Functions:	Normal Line Scanning

2. The line scans are carried out as for POF 5.
3. Nodding is not performed.
4. Chopping is performed, in the direction parallel to the direction of the telescope scan..
5. The telescope is scanned continuously across the sky at a constant rate.
6. The telescope scan motion is effectively frozen during one chop cycle. It is required that the signal from an individual chop cycle be ascribed to an interval of less than 1 arcsec. on the sky (roughly 1/20th of a PSW beam). The maximum allowed scan rate in arcsec./sec. is then the same as f_{chop} in Hz: e.g., for f_{chop} = 1 Hz, the maximum scan rate is 1" s^{-1}.

Detector sampling, on-board processing and data rate: As for POF 5.

Instrument and Spacecraft Functions used and their parameters:

Instrument Function: Photometer Chop			
Parameter	**Range of values**	**Nominal value**	**Comments**
Chop frequency (f_{chop})	0.2 (TBC) - 1 Hz	1 Hz	1-Hz limit when chopping in both axes.
Chop direction	Parallel to scan direction	Parallel to scan direction	
Chop throw ($\Delta\theta_{chop}$)	Any value within the BSM range (± 130” in Y; ± 30” in Z)	TBD but likely to be ~ 1 FWHM at PLW = ~ 40”	
Number of chop cycles per nod position (N_{chop})	N/A	N/A	Not specified in this mode
Spacecraft Function: Line Scanning			
Scan mode	As for POF 5	As for POF 5	
Scan direction (ϕ_{scan})	As for POF 5	As for POF 5	
Scan rate ($\dot{\theta}$)	As for POF 5	1 arcsec. s^{-1}	
Angular length of each line scan (D_1)	As for POF 5	As for POF 5	
Number of lines (N)	As for POF 5	As for POF 5	
Angular distance between successive steps (d_2)	As for POF 5	As for POF 5	
OFF position	As for POF 5	As for POF 5	

Table 3.10: Spacecraft and Instrument Functions for POF 6.

3.1.7 POF 7: Photometer Peak-Up

Purpose: This Observatory Function is designed to allow SPIRE to peak up the pointing on a sufficiently strong point-like source.

Description:

1. POF 6 is composed of the following instrument and Spacecraft Functions

Instrument Function:	Photometer-Chop
Spacecraft Functions:	Nod

2. The SPIRE BSM executed a 5-point cross of POF 1 observations centred on the source, with angular separation $\Delta\theta_5$. A five-point is chosen so that a simple on-board fitting routine can be implemented by the DPU.
3. The offset of the source with respect to the commanded pointing is computed by the DPU using the recorded data.
4. The calculated pointing offsets ($\Delta\theta_Y$ and $\Delta\theta_Z$) are (a) implemented by the BSM (baseline) or (b) transmitted to the spacecraft AOCS.
5. If (b), the AOCS checks that the required telescope movement is within the acceptable limits and executes it.
6. (a) The AOCS transmits a message to SPIRE confirming that the pointing correction has been implemented, or (b) SPIRE waits for a standard period of time to elapse before flagging the data as valid
7. The need for this function is TBD. It is not needed for very bright objects (carrying out a small map is quick compared to overheads from slewing etc.). Nor is it practical for very faint objects (poor S/N of the 5-point data would lead to inaccurate offset calculation). It is therefore only likely to be useful for a

particular band of source strengths (exact limits TBD).

An alternative approach might be to establish an accurate pointing model covering the available sky window by regular observation of a selection of bright point sources, calculating the pointing offsets on the ground, and uplinking the derived pointing model parameters to the spacecraft. This would depend on the availability of good pointing sources distributed over the viewable sky, and on the pointing characteristics being highly repeatable and dependent only on the pointing direction (not on the pointing history).

Instrument and Spacecraft Functions used and their parameters: See Table 3.11.

<table>
<tr><th colspan="5">Instrument Function: Photometer Chop</th></tr>
<tr><th>No.</th><th>Parameter</th><th>Range of values</th><th>Nominal value</th><th>Comments</th></tr>
<tr><td>1</td><td>Chop frequency (f_{chop})</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>2</td><td>Chop direction</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>3</td><td>Chop throw ($\Delta\theta_{chop}$)</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>4</td><td>Number of chop cycles per nod position (N_{chop})</td><td>N/A</td><td>N/A</td><td>Not specified in this mode</td></tr>
<tr><th colspan="5">Instrument Function: Photometer Jiggle</th></tr>
<tr><td>1</td><td>Jiggle pattern offset of each of the four neighbour positions from the centre ($\Delta\theta_5$)</td><td>3 – 10 arcsec.</td><td>6 arcsec.</td><td>6 positions are observed: centre + NSEW + centre again. This is the only difference between the peak-up observation and a seven-point.</td></tr>
<tr><td>2</td><td>Number of chop cycles/ jiggle position (N_{chop})</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>3</td><td>Number of jiggle patterns /nod position (N_{jigpat})</td><td>As for POF 2</td><td>As for POF 2</td><td></td></tr>
<tr><th colspan="5">Spacecraft Function: Nod</th></tr>
<tr><td>1</td><td>Nodding</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>2</td><td>Dwell time on each nod position (t_{dwell})</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>3</td><td>Nod direction</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>4</td><td>Nod throw ($\Delta\theta_{chop}$)</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
<tr><td>5</td><td>Total number of nod cycles (N_{nod})</td><td>As for POF 1</td><td>As for POF 1</td><td></td></tr>
</table>

Table 3.11: Spacecraft and Instrument Functions for POF 7.

3.1.8 Summary of photometer observing modes

POF	Chop	Jiggle	Nod	Scan	Raster
1	Yes	No	Yes	No	No
2	Yes	Yes	Yes	No	No
3	Yes	Yes	Yes	No	No
4	Yes	Yes	Yes	No	Yes
5	No	No	No	Yes	No
6	Yes	No	No	Yes	No

Table 3.12: Summary of parameters for photometer observing modes.

3.1.9 POF 8: Photometer Calibrate

It is expected that the photometer calibrator will be operated at intervals of several tens of minutes to an hour . Its function is to present a repeatable signal to the detectors. This will allow characterisation of :

(i) any responsivity or system gain drifts;
(ii) any variation of the detectors' responsivity with radiation loading (e.g., non-linear response when viewing very bright sources).

In operation, it will be powered by a pre-selected waveform, and the corresponding signals will be recorded. A typical duration of the whole sequence will be ~ 10 sec. The BSM must be fixed at its rest position, and the telescope pointing must also be fixed so that the only signal modulation is from the calibrator.

PCAL operations are to be incorporated within the other POFS (at the start and end of each observation, and within the observation if necessary - e.g., to enable calibrator flashes to be interspersed between the rows of line scanning observations).

Instrument and Spacecraft Functions used and their parameters: See Table 3.13.

Instrument Function: Photometer Calibrate				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chopping	OFF	N/A	Nodding off also
2	PhotCal	ON	A preset sequence of drive currents	
Spacecraft Function: Pointed				
1	Pointed	(θ_{YP}, θ_{ZP})	N/A	The spacecraft is not required to do anything else

Table 3.13: Spacecraft and Instrument Functions for POF 8.

3.1.10 SPIRE-PACS Parallel Mode

This is a particular implementation of POF5. It is described in detail in RD 2.

3.2 Observatory Functions for Spectrometer

The spectrometer mirror mechanism can be operated in two modes: *Continuous Scan* or *Step-and-Integrate*.

- In principle, *Step-and-Integrate*, provides superior S/N because the spectrometer calibrator does not need to be operating, thereby reducing photon noise by a factor of √2.
- *Continuous Scan* is usually the optimum operating mode for an FTS because it minimises the effects of 1/f noise and also reduces the time overhead associated with moving the mirror between positions.
- *Step-and-Integrate* may be needed for low resolution observations if the spectrometer mechanism velocity control does not meet its stringent stability requirement
- In the event of a total inability to scan the FTS mirrors – or in the event of or a serious loss of ability to telemeter data – *Step-and-Integrate* should still be feasible.

Which mode is better in practice thus depends on the overall performance and noise characteristics of the system. Based on ground testing of SPIRE, the performance of the FTS in continuous scan mode is to spec. or better, and this mode will be adopted as the baseline for all FTS observations (to be verified in PV phase). Depending on the detailed evaluation of the performance in PV phase, it may be that for low resolution spectrometer observations, *Step-and-Integrate* is optimum and *Continuous Scan* is used for high resolution.

Either of these modes of operation may be used to make one of two types of spectrometer Observation: Point Source Spectrometry or Mapping Spectrometry.

The Observatory Functions for the spectrometer are listed in Table 3.14. Each of these can be implemented at a single telescope pointing or at multiple telescope pointings. RD 5 defines the intermediate and fully sampled positions as well as the raster positions that have been adopted as baseline.

OBSERVATORY FUNCTION	Name	Comments
SOF1	Continuous Scan (baseline)	Point source/sparse map Accurate pointing & source posn. assumed
SOF3	Step-and-Integrate (not baseline)	Point source/sparse map Accurate pointing & source posn. assumed
SOF2 SOF2_int	Continuous Scan (baseline)	Field mapping; intermediate image sampling Field mapping; fully sampled image
SOF4 SOF4_int	Step-and-Integrate (not baseline)	Field mapping; fully sampled image Field mapping; intermediate image sampling

Table 3.14: Spectrometer Observatory Functions.

These are described below, and more details can be found in the SPIRE OM.

3.2.1 SOF1: Point Source Spectrum (Continuous Scan)

Purpose: To take a spectrum of a point source that is well centred on the central detectors of the FTS arrays and/or simultaneously obtain a sparse map of an area roughly 2 arcmin. in diameter. For sparse mapping of larger areas, a raster of multiple SOF1s is implemented.

Description:

1. This Observatory Function is composed of the following instrument and Spacecraft Functions: Instrument Function: Spectrometer Continuous Scan ; Spacecraft Function: Pointed

2. If not already powered on, the FTS calibrator is switched on to a pre-defined level and allowed to stabilise for typically 10 minutes.
3. The telescope is pointed at a known source position, with the source lying on the central detector of the short-wavelength array.
4. In this mode, the Beam Steering Mechanism is not operating and the FTS scan mirror is moved at constant speed to modulate the signal. The radiation frequencies to be detected are encoded as audio frequencies in the detector output.
5. The FTS mirror mechanism is scanned over the required range with the velocity controlled by the drive electronics. The scan will take approx. 70 seconds to complete for the high resolution spectra. The detectors and the position sensor are read out asynchronously whilst the mechanism is moving – i.e. the default is to time-sample the FTS mechanism position.
6. Each interferogram for each detector may be stored in the DPU memory or packetised and telemetered to the CDMS in near real time. The maximum amount of data per scan will be about 750 kbytes for all 56 detectors for high resolution spectra if sampled at 4 μm intervals at 16 bits with no data compression (equivalent to 80 Hz sampling). The data rate into the DPU is ~ 80 kbs for all continuous scanning operations – it will be adjusted to match the total allowed downlink rate from Herschel.
7. The scan is repeated until the desired total integration time has been reached.

Instrument and Spacecraft Functions used and their parameters: See Table 3.15

Instrument Function: Spectrometer Continuous Scan

No.	Parameter	Range of values	Nominal value	Comments
1	Mirror velocity	0.02-0.1 cm s^{-1} (depends on stability of the instrument and the response of the detectors)	0.05 cm s^{-1}	
2	Scan Range	-0.35 to +3.5 cm	Low res: ± 0.15 cm (R = 1 cm^{-1}) Med res.: ± 0.6 cm (R = 0.25 cm^{-1}) High-res.: -0.15 to +3.5 cm (R = 0.04 cm^{-1})	These scan ranges allow some extra range for mirror turn-around. Times per scan are: Low res: ~ 6 s Med res.: ~ 24 s High res.: ~ 67 s
3	Total number of scans	Minimum of 4 (two forward, two back) for comparison, deglitching, and return to home. Maximum: no specific maximum (but practical limit imposed by max. allowed duration of a telescope pointing).		
Spacecraft Function: Pointed				
1	Pointed	(θ_{YS}, θ_{ZS})	N/A	The spacecraft is not required to do anything else except to track the source.

Table 3.15: Spacecraft and Instrument Functions for SOF 1.

3.2.2 SOF2: Fully Sampled Spectral Map (Continuous Scan)

Purpose: To take a spectrum of a region of sky or an extended source that is within the FOV of the spectrometer – i.e. less than 2.6 arcmin circular. This is achieved by using the beam steering mirror to perform a low-frequency jiggle and taking one or more interferograms at each point of the jiggle pattern. For fully-sampled mapping of larger areas, a raster of multiple SOF2s is implemented.

Description: This is an example Observatory Function for a unapodised resolution of 0.4 cm^{-1}. The distance the FTS mechanism has to scan will be set by the required resolution.

1-3: As for SOF1

5. The BSM is used to make an 16-point jiggle map similar to POF 3, but the specific jiggle positions are optimised for the FTS arrays. The mirror is held at each position while several FTS scans are carried out.
6. At each jiggle position the FTS mirror mechanism is scanned. The minimum number of interferograms required per position is 4.
7. The data rate is as for SOF1
8. The jiggle/scan is repeated until the desired integration time has been reached for the whole map.

Instrument Function: Spectrometer Scan				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Prime detector	As for SOF1		
2	Mirror Velocity	As for SOF1		
3	Scan Range	As for SOF1		
Instrument Function: Spectrometer Jiggle				
1	Jiggle pattern	16-point with positions ($\Delta\theta_Y,\Delta\theta_Z$) with respect to the pointed position	$\Delta\theta_Y,\Delta\theta_Z$ offsets as defined in RD 5.	
2	Number of FTS scans per jiggle position	Min = 4 Max = not specifically defined		
Spacecraft Function: Pointed				
1	Pointed	As for SOF1		

Table 3.16: Spacecraft and Instrument Functions for SOF 2.

3.2.3 SOF2_int: Spectral Map with intermediate image sampling (Continuous Scan)

Purpose: As for SOF2 except that the image is not fully sampled in order to reduce the observation time. The spatial sampling is intermediate between the sparse map provided by a SOF1 (33, 51 arcsec for SSW/SLW) and the full sampling provided by SOF2 (8, 13 arcsec for SSW/SLW). The sampling for SOF2_int is 16, 25 arcsec for SSW/SLW.

Description: As for SOF2 with the sole exception that a 4-point Jiggle is implemented instead of a 16-point Jiggle.

3.2.4 SOF3: Point Source Spectrum (Step-and-Integrate)

Purpose: To take a spectrum of a point source that is well centred on the central detectors of the FTS arrays. This mode is not planned to be used unless there are problems in flight with the operation or data quality when using SOF 1.

Description:

1. This Observatory Function is composed of the following instrument and Spacecraft Functions:
   Instrument Function: Spectrometer Step Scan
   Spacecraft Function: Pointed
2. As for SOF1.
3. As for SOF1.
4. In this mode, the mirror is placed sequentially at a range of positions to complete a scan. The BSM is operating at some suitable chop frequency (nominally 2 Hz) and at least two chop cycles are recorded at each spectrometer mirror position to build up the interferogram. The minimum optical path difference step size is given approximately by $1/2\sigma$ where σ is the wavenumber corresponding to the maximum radiation frequency to be detected. With σ = 50 cm^{-1} (corresponding to 200 µm wavelength), the maximum optical path difference step size is 100 µm. It is normal to over-sample by a factor of 4 or 5 with respect to this critical value. A nominal value of 20 µm is therefore appropriate to ensure good sampling of the interferogram. The design of the SPIRE FTS is such that there is a factor of four folding between the movement of the mirror and the change of optical path difference – the minimum step size must therefore be about 5 microns. In fact the optical encoder to be used allows steps in increments of 2 microns so the step size can either be 4 or 6 microns – here we take 6 µm.

   The number of samples per interferogram depends on the required resolution:

Low resolution (R = 2 cm^{-1}):	Scan range	= -0.07 cm to + 0.07 cm = 1,400 µm
	Step size	= 6 µm
	No. of steps	= 233
Medium resolution (R=0.4 cm^{-1})	Scan range	= -0.35 cm to + 0.35 cm = 7,000 µm
	Step size	= 6 µm
	No. of steps	= 1167
High resolution (R=0.04 cm^{-1})	Scan range	= -0.35 cm to + 3.5 cm = 38,500 µm
	Step size	= 6 µm
	No. of steps	= 6417

5. The scan is repeated until the desired total integration time has been reached.

Detector sampling, on-board processing and data rate: As for POF 1. The separate spectrometer mirror positions are equivalent to separate telescope pointing positions in a spatial raster scan.

Instrument Function: Spectrometer Scan (Step-and-Integrate)				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chop frequency	As for POF 1		
2	Chop direction	As for POF 1		
3	Chop throw	As for POF 1		
4	Mirror Velocity	Zero except when moving between positions. A possible implementation is that the mirror will actually be scanned continuously at a very low speed.	0	
5	Scan Range	As for SOF1		
6	Mirror Step	2 - 26 μm	4 or 6 μm (TBC)	5 μm corresponds to 10 samples per cycle at 200 μm wavelength. The optical encoder is incremented in steps of 2 μm
7	Total number of scans	1 - TBD	1 (TBC)	The integration time per step must be at least two chop cycles. At 2-Hz, this is 1 sec. per point. The total number of points for a low-resolution scan is ~240 so each scan will take a minimum of four minutes – a reasonable value. For a high resolution scan the number of steps per scan is ~6400 or nearly two hours – this probably precludes the use of step and look for high resolution spectra.
Spacecraft Function: Pointed				
1	Pointed	(θ_{YS}, θ_{ZS})	N/A	The spacecraft is not required to do anything else except track the source.

Table 3.17: Spacecraft and Instrument Functions for SOF 3.

3.2.5 SOF4: Fully Sampled Spectral Map within FOV (Step-and-Integrate)

Purpose: To take a spectrum of a region of sky or an extended source that is within the FOV of the spectrometer – i.e. less than 2.6 arcmin circular. This is achieved by using the beam steering mirror to perform a low-frequency jiggle and taking one or more interferograms at each point of the jiggle pattern. This mode is not planned to be used unless there are problems in flight with the operation or data quality when using SOF 2.

Description: This is an example Observatory Function for a resolution of 0.4 cm^{-1}. The distance the FTS mechanism has to scan will be set by the required resolution.

1-6: As for SOF1

7. The BSM is used to make an n-point jiggle map as in POF 3. The mirror is held at each position while several FTS scans are carried out.
8. For full sampling at all wavelengths, n = 25. Considering the simplified case of square-packed horns, the step size must be $0.5\lambda/D = 9''$ at 250 μm and the number of steps must accommodate the need to cover the distance between two beams at 350 μm: $2\lambda/D = 45''$. Five steps in each orthogonal direction are thus required. The geometry of the juggle pattern is hexagonal for the hexagonally packed feedhorns, but the number of steps required is still 25.
9. At each jiggle position the FTS mirror mechanism is stepped exactly as in SOF3.
10. The jiggle/scan is repeated until the desired integration time has been reached for the whole map.

Instrument Function: Spectrometer Scan (Step-and-Integrate)				
No.	**Parameter**	**Range of values**	**Nominal value**	**Comments**
1	Chop frequency	As for POF 1		
2	Chop direction	As for POF 1		
3	Chop throw	As for POF 1		
4	Mirror Velocity	Zero except when moving between positions. A possible implementation is that the mirror will be scanned continuously at a very low speed.	0	
5	Scan Range	As for SOF1		
6	Mirror Step	2 – 26 μm	4 or 6 μm (TBC)	See comments for SOF3.
7	Total number of scans	1 - TBD	1 (TBC)	See comments for SOF3
Spacecraft Function: Pointed				
1	Pointed	$(\theta_{YS}, \theta_{ZS})$	N/A	The spacecraft is not required to do anything else except track the source.

Table 3.18: Spacecraft and Instrument Functions for SOF 4.

4. DEGRADED OPERATIONS

A criticality analysis has been carried out at the instrument level to assess what extra operating modes may be required in the event of a failure or partial failure of one of the SPIRE sub-systems. The need for the following degraded operating modes has been identified:

4.1 Automatic Cooler Recycling

At present the baseline is that cooler recycling will be undertaken during one of the ground contact times thus making use of the times when observing is restricted or not possible. If the cooler does not have the ability to operate for the required length of time due to increased thermal load or some other reason, it may become necessary to undertake cooler recycling more frequently than this. However if the cooler needs more frequent recycling it may be that the most efficient way of operating is to have the recycle done autonomously under control of the DPU alone. This mode of operation must be planned for and thoroughly tested before launch.

4.2 Slow Chop Mode

If the BSM suffers a failure that prevents it from chopping at the default frequency due to sticking or excessive dissipation, it may be that it may have to be chopped very much more slowly. This implies that the control circuitry and algorithms must be capable of driving the BSM at any frequency from DC up to the maximum allowable by the design. A range of chop frequencies must be identified and the instrument response at these frequencies characterised before launch.

4.3 BSM Open Loop

In the event of a failure of the position sensor on the BSM chop axis, it must still be possible to operate the BSM by commanding the current to the actuators directly. This mode of operation may lead to a loss of efficiency as the chopping mirror will not be under control and may take some time to become stable after movement. The behaviour of the BSM under open loop control must be characterised and suitable current demand algorithms devised to allow at least the chopped mode to be carried out in the event of loss of the chop axis position sensor. In the event of a fault preventing closed loop control, the relevenat operating parameters for open loop operation will need to be determined in flight.

4.4 Single Axis BSM Operation

It may be that one axis of the BSM stops working during the mission. In this case it must be possible to use the other axis on its own to chop or, if the chop axis is lost, at least to pixel-swap on one of the detector arrays. It may be that there is some mechanical crosstalk between the axes and demand will be required on both axes during nominal operation to achieve accurate positioning. If this is the case the operation of each axis in the absence of the other must be possible and this mode of operation fully characterised before launch.

4.5 Slow scanning of the FTS mirrors

If there is, for any reason, a problem with the amount of data that can be telemetered to the ground, one way of reducing the data rate from the spectrometer is to slow down the scan rate for the FTS mirrors. Also, if there is any problem with the mirror drive, sticking or high dissipation, it may be that this also could be alleviated by slowing down the scan rate. A series of FTS mirror scan speeds must be allowed for in the design and the instrument response at each speed characterised before launch.

4.6 Open loop operation of the FTS mechanism

In the event of loss of the FTS mechanism position sensor the mirrors can still be driven by use of direct command of the current to the actuator. This mode of operation will lead to loss of fidelity in the reconstructed spectrum as the position of the mirrors will need to be inferred rather than directly measured.

However some information should be recoverable. The behaviour of the FTS mechanism in open loop control must be characterised and suitable current demand algorithms devised to allow full range scanning and step and look operation.

4.7 Selection of pixels for telemetry

If there is, for any reason, a problem with the amount of data that can be telemetered to the ground, another way of reducing the data rate is to telemeter the data from a limited subset of the detectors in either the photometer or the detector. The detectors that will be telemetered under these circumstances must be identified and the appropriate selection procedures coded into the data reading hardware and/or on board software. These low data rate modes must be fully implemented and tested before launch.

4.8 Spectrometer Operation without calibrator

In the event of the loss of the spectrometer calibrator the dynamic range in the signal will be very much higher and more bits may be required to encode the data. This may violate the constraint on the amount of data that can be telemetered. A well developed scenario must be developed that allows as much data as possible to be sent to the ground in spectrometer mode. This may involve lossless data compression; selection of only a few detectors and/or slowing down the spectrometer mirrors. This mode of operation must be fully implemented and tested before launch.