

# The SPIRE Analogue Signal Chain and Photometer Detector Data Processing Pipeline

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Changes and additions with respect to Issue 6 (Nov. 2008) are in blue text

Changes and additions with respect to the Dec. 20 2008 draft are in dark red text

Updates to Issue 6:

- incorporation of Darren's note on electrical crosstalk due to bias pull-down in Section 5.2;
- clarifications and change of terminology in the section on demodulation (Section 6);
- confirmation that  $K_4$  can be incorporated into  $K_1$  and  $K_2$  (Section 7.3);
- a few minor wording changes.

Additional updates to Issue 7 draft of Dec. 20 2008 based on:

- scan-map and jiggle-map review checklists (Darren Dowell, March 8 2009);
- draft technical note *Phase ups and phase correction in the pipeline*, Bruce Swinyard, 12 March 2009 (still under discussion - the manner in which the small variations in LIA phase from detector to detector is to be handled is still under review and the scheme presented in Section 3.9 should be taken as the baseline for now);
- standardised terminology conventions outlined in Matt Griffin e-mail of 7 April, listed in Section 2 and adopted throughout;
- nominal spectrometer bias frequency changed from 190 to 160 Hz;
- various other minor changes.

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## 1. Introduction

The purpose of this note is to describe the propagation of the SPIRE science data signals from the **bolometers** through to the digitised samples transmitted to the ground, and to outline the methods by which the measured **bolometer** voltages are to be converted to astronomical signals.

Section 2 contains a list of the symbols used in the document.

Section 3 describes the analogue signal chains for both the photometer and FTS, and is largely based on information in the *DCU Design Document (DCU DD)* [1]. It concludes with a description of how the Photometer and Spectrometer Data Timeline (PDT and SDT) products (bolometer voltage and resistance) are to be derived from the telemetry data. This section applies both to the photometer and FTS pipelines, the only differences being in the values of various parameters and in the form of some of the transfer functions. Subsequent stages of the two pipelines will have some common features, but will be different in many respects. The FTS pipeline following the derivation of the Spectrometer Detector Timeline (SDT) products is described in detail in [2].

Section 4 deals with the transient response of the photometer signal chain, taking into account the characteristics of the **bolometers** and the analogue filter, and the observing modes.

The SPIRE observing modes are described in *Operating Modes for the SPIRE Instrument* [3]. The photometer pipelines (one for scan map observations and one for chopped/nodded observations) will operate on the corresponding **bolometer** and housekeeping timelines to produce **bolometer** data timelines calibrated in terms of in-beam source flux density.

Two options are considered for the photometer pipelines:

- (ii) an “empirical” approach (Sections 5 and 6), similar to the data processing schemes traditionally used for bolometer instruments, in which the **bolometer** voltages are used directly to derive the astronomical signals, and which requires empirically-based corrections to be made in order to correct for thermal effects and non-linear response;
- (i) a “model-based” approach which uses physical models of the bolometers and their operating temperatures, involves calculation of the absorbed radiant power as an intermediate step in the derivation of the astronomical signals, and is in principle capable of correcting for both thermal variations and **bolometer** non-linearity.

The model-based approach has potential advantages in that it automatically takes into account the detector bias conditions, non-linear response to strong sources, and any variations in **the** bath temperature and background radiation from the instrument or the telescope. But implementing the model-based pipeline may be challenging, at least in the first instance, so it is planned that the empirical pipeline be implemented in full and available at the start of the mission. The empirical pipeline will therefore be implemented by the SPIRE ICC in preparation for launch and SPIRE operations. It may eventually be superseded eventually by the model-based pipeline.

## 2. Terminology and list of symbols

In this document and/or the other pipeline documents, the following terms and definitions are adopted when referring to the SPIRE science data channels:

**Bolometer:** One of the bolometric detectors on a BDA, designed to be sensitive to submillimetre radiation

**Dark Bolometer:** One of the bolometric detectors on a BDA, identical in all respects to a bolometer except that it is designed to be blanked off from the incoming submm radiation (indicated by the letter D in the BDA EIDP)

**BDA Thermistor:** One of the thermistors attached to a BDA, designed to be sensitive to the  $^3\text{He}$  stage temperature at the BDA but insensitive to radiant power (indicated by the letter T in the BDA EIDP)

**BDA Resistor:** One of the BDA-mounted resistors used in place of bolometers, designed to provide an electrical input equivalent to a bolometer but insensitive either to temperature or radiant power (indicated by the letter R in the BDA EIDP)

**PTC Thermistor:** As for a BDA Thermistor, but mounted in the PTC unit.

**Channel:** The end-to-end chain between any of the above and the corresponding data stream, (e.g., bolometer channel, dark bolometer channel, BDA thermistor channel, etc.)

**Pixel:** An individual point in a map. The term pixel should not refer to a hardware entity and is not synonymous with "bolometer" since there is not a one-to-one correlation between a pixel in the map and a particular detector.

List of Symbols	
Symbol	Definition
$a$	Bolometer slow response amplitude factor
$A_{\text{Tel}}$	Telescope effective collecting area
$C_{\text{H}}$	Capacitance of the harness between the detector and JFET input
$\mathbf{C}_{\text{elec}}$	Electrical crosstalk matrix
$\mathbf{C}_{\text{opt}}$	Optical crosstalk matrix
$DATA$	16-bit ADC output value corresponding to a detector voltage value
$e_{ij}$	Coefficient of electrical crosstalk matrix linking output of bolometer $i$ to bolometer $j$
$f_{\text{b}}$	Bias modulation frequency
$f_{\text{samp}}$	Bolometer sampling frequency
$G_{\text{d}}$	Bolometer dynamic thermal conductance ( $dW/dT$ )
$G_{\text{d-300mK}}$	$G_{\text{d}}$ at 300 mK
$G_{\text{LIA}}$	Gain of signal chain between JFET output and low-pass filter output
$G_{\text{tot}}$	Total gain of analogue signa chain from JFET output to the ADC
$H_{\text{Bol}}(\omega_{\text{s}})$	Bolometer transfer function with respect to modulated radiant power
$H_{\text{BPF}}(\omega_{\text{b}})$	Transfer function of the DCU band-pass filter
$H_{\text{Demod}}(\phi)$	Square-wave demodulator transfer function as a function of input phase difference
$H_{\text{H}}(\omega_{\text{b}})$	Transfer function of the harness between the bolometer and JFET input
$H_{\text{JFET}}(\omega_{\text{b}})$	Transfer function of the JFET
$H_{\text{LPF}}(\omega_{\text{b}})$	Transfer function of the DCU low-pass filter
$H_{\text{o}}$	Bandpass filter peak gain
$i_{\text{b}}(t)$	Bias current as a function of time
$I_{\text{b}}$	Bias current amplitude
$I_{\text{b-RMS}}$	RMS value of bias current
$I_{\nu}$	Sky surface brightness

$j$	$\sqrt{-1}$
$K_1, K_2, K_3$	Parameters defining function fitted to variation of overall system responsivity ( $dS/dV$ ) with operating point voltage
$K_4$	Constant of proportionality relating RSRF-weighted flux density to monochromatic flux density
$K_{\text{Beam}}$	Beam correction factor for a uniform disk source
$K_C$	Spectral index (colour) correction factor to convert measured flux density to a different assumed source spectral index
$n_{\text{samp}}$	Number of <b>bolometer</b> samples per BSM position in chopped mode
$o_{ij}$	Coefficient of optical crosstalk matrix linking output of <b>bolometer</b> $i$ to <b>bolometer</b> $j$
$OFFSET$	4-bit offset used to generate offset voltage to be subtracted from LPF output voltage
$P$	Electrical power dissipated in the bolometer
$Q(t)$	Total radiant power absorbed by a bolometer as a function of time
$Q_B$	Background power absorbed by a bolometer
$Q_C$	Radiant power from the astronomical calibration source absorbed by a bolometer
$Q_S$	Radiant power from the astronomical source absorbed by a bolometer
$r_C$	Angular radius of planetary calibration source
$R_b$	Series resistance between bias supply and the bolometer load resistors
$R_d$	<b>Bolometer</b> resistance
$R_L$	Total load resistance
$R_S$	Bolometer resistance parameter
$R(\nu)$	Relative Spectral Response Function of a photometer band
$S_S(\nu)$	Astronomical source in-beam flux density at frequency $\nu$
$S_C(\nu)$	Astronomical calibration source in-beam flux density at frequency $\nu$
$S_{oR}, S_{oR}$	Fictitious flux density offsets measured when chopping in the presence of an ambient background that is different in the two chop positions
$S_b$	Background sky in-beam flux density
$S_A, S_B$	Demodulated flux density measured for nod positions A and B
$t$	Time
$t_{\text{wait}}$	Delay between issue of BSM move command and first <b>bolometer</b> sample for the new position
$T_b$	Period of bias waveform ( $= 1/f_b$ ) [not to be confused with temperature]
$T_g$	Bolometer material band-gap temperature
$T_o$	Bolometer bath temperature
$T_{L-1}$	SPIRE FPU Level-1 temperature
$T_{\text{tel}}$	Telescope temperature
$v_b(t)$	Bias voltage as a function of time
$V_b$	Bias voltage amplitude
$v_d(t)$	Voltage across <b>bolometer</b> as a function of time
$U$	Bolometer small signal responsivity ( $V_S/Q_S$ )
$V_{\text{ADC}}$	Voltage input to the ADC, from which <i>DATA</i> is derived
$V_{\text{BPF}}$	Amplitude of voltage at the band-pass filter input
$V_d$	Amplitude of voltage across <b>bolometer</b>
$V_{\text{d-RMS}}$	RMS value of voltage across <b>bolometer</b>
$V_{\text{Demod}}$	DC voltage amplitude at demodulator output
$V_{\text{JFET}}$	Amplitude of the voltage at the JFET output
$V_{\text{JFET-RMS}}$	RMS voltage at the JFET output
$V_{\text{LPF}}$	Amplitude of voltage at the low-pass filter input
$V_o$	Fixed bolometer offset voltage used in flux density conversion.
$V_{\text{Offset}}$	Voltage level generated by the DAC from <i>OFFSET</i> , and subtracted from the LPF output voltage
$V_S$	Decrease in RMS <b>bolometer</b> voltage at the operating point due to the astronomical signal
$V_{\text{th}}(t)$	Array thermometry timeline used to remove correlated noise from the bolometer timelines
$W$	Total power dissipated in the bolometer

$\alpha_C$	Astronomical calibration source power law spectral index
$\alpha_S$	Astronomical source power law spectral index
$\alpha_{\text{nom}}$	Nominal source spectral index for which SPIRE flux densities will be quoted
$\beta$	Bolometer thermal conductivity power law index
$\Delta V_{\text{JFET-RMS(1-bit)}}$	Change in RMS voltage at the JFET output that corresponds to a 1-bit change in the value of <i>DATA</i>
$\Delta\phi_d; \Delta\phi_{\text{nom}}$	Phase difference between demodulator reference and input signals for arbitrary bolometer impedance (d) and nominal dark sky value (nom)
$\Delta S$	Statistical uncertainty in flux density
$\phi$	Bolometer temperature normalised to the bath temperature
$\eta(\nu)$	Overall efficiency for coupling between flux density at the telescope aperture and power absorbed by a bolometer
$\tau_B, \tau'_B$	Bandpass filter time constant parameters
$\theta_{\text{Beam}}$	Beam width at FWHM
$\tau_1$	Bolometer nominal time constant
$\tau_2$	Bolometer “slow” time constant
$\nu$	FIR/submm radiation frequency
$\nu_0$	Radiation frequency characterising a photometer band, and for which the astronomical flux density is quoted
$\tau_H$	Time constant defined by the JFET harness capacitance and the parallel combination of the bolometer and load resistances
$\sigma$	Signal-to-noise ratio
$\omega_b$	Angular frequency of bolometer bias voltage
$\omega_S$	Angular frequency of bolometer signal modulation
$\Omega_{\text{Beam}}$	Beam solid angle

### 3. The SPIRE on-board electronics chain

The electrical design of the SPIRE detector subsystem and the on-board electronics is described in detail in the *SPIRE Design Description* document [4], and in the *DCU DD*. This section outlines the main features and functions of the system.

#### 3.1 Bolometer bias and readout

Figure 1 shows the essential features of the bolometer bias and readout electronics used in SPIRE. The bolometer is biased (heated, by applied electrical power  $P$ , to its optimum operating temperature of around  $1.3T_0$ ) by a sinusoidal excitation at angular frequency  $\omega_b$ , corresponding to a frequency,  $f_b = \omega_b/2\pi$ , of around 100 Hz. The sinusoidal bias excitation is applied symmetrically via the two load resistors,  $R_{L+}$  and  $R_{L-}$ , each with nominal resistance  $R_L/2$  (typically  $\sim 8 \text{ M}\Omega$  each, except for the SLW array for which the value is typically  $12 \text{ M}\Omega$ ). Each array has one bias supply which is common to all bolometers. There is some series resistance,  $R_b/2$ , between each side of the bias supply and the load resistors due to the output resistance of the bias circuit ( $51 \text{ k}\Omega$ ) and the much smaller harness impedance. The resistance of a SPIRE bolometer at the operating point,  $R_d$ , is typically  $3 \text{ M}\Omega$ . The bias excitation is much faster than the thermal time constant, so that bias itself does not produce a temperature modulation, and the impedance of the bolometer at the bias frequency is also purely resistive. This AC biasing is preferred over DC bias as it up-converts the signal information to the bias frequency, getting well above the  $1/f$  noise knee of the JFET readout amplifiers. With this arrangement, because of the inherently low  $1/f$  noise of the bolometers, the  $1/f$  noise knee of the system can be very low (less than 0.1 Hz).

The bolometer signals are fed to a pair of JFET source followers, and the JFET outputs are connected via the long cryoharness to the warm electronics.

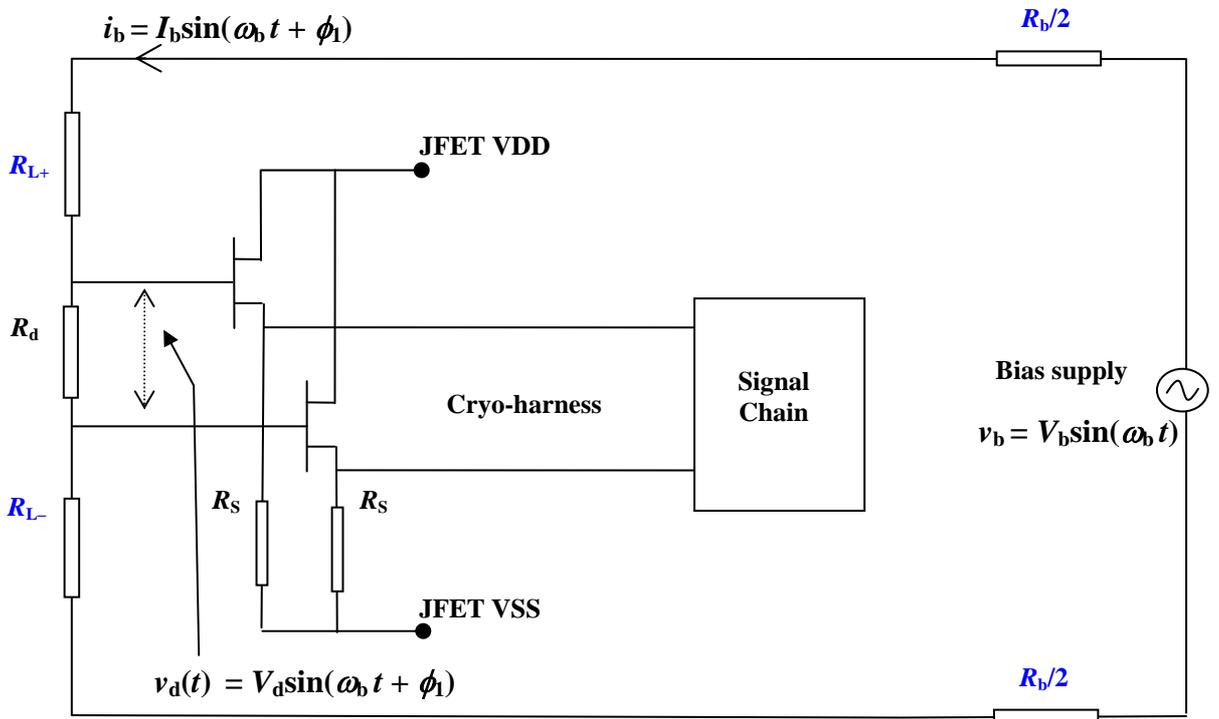


Figure 1: SPIRE bolometer bias and readout circuit

Let the applied AC bias voltage be

$$v_b(t) = V_b \sin(\omega_b t), \quad (1)$$

producing a bias current, flowing through the load resistor and the **bolometer**, given by

$$i_b(t) = I_b \sin(\omega_b t + \phi_1), \quad (2)$$

where  $\phi_1$  is some phase difference between output of the bias generator in the warm electronics and the bolometer current.

The corresponding AC voltage across the **bolometer** is,

$$v_d(t) = V_d \sin(\omega_b t + \phi_1), \quad (3)$$

where

$$V_d = I_b R_d.$$

The operating point on the load curve corresponds to the RMS values of the **bolometer** voltage and current:

$$V_{d-RMS} = \frac{V_d}{\sqrt{2}} \quad I_{b-RMS} = \frac{I_b}{\sqrt{2}} \quad P = V_{d-RMS} I_{b-RMS}. \quad (4)$$

The amplitude of bolometer signal,  $V_d$ , will vary if the radiant power on the **bolometer** is being modulated (for instance by chopping or telescope scanning in the case of the photometer or movement of the scan mirror in the case of the spectrometer. For a radiant signal modulated at frequency  $\omega_s$  ( $\ll \omega_b$ ) we will represent the corresponding signal amplitude as  $V_d(\omega_s)$ .

### 3.2 Block diagram of the analogue electronics chain

A model of the complete SPIRE signal chain is shown in Figure 2. The **bolometer** signals are de-modulated by individual lock-in amplifiers (LIAs). An LIA comprises a bandpass filter and a square wave demodulator, followed by a low-pass filter. The output of the LIA is nominally a DC voltage proportional to the RMS value of the voltage at the bolometer output. The LIA outputs are multiplexed and sampled for telemetry to the ground. The bias waveform is obtained by dividing down the frequency of an on-board oscillator, and its frequency is given by  $f_b = 2\pi 10^7 / (512 * N)$  where  $N$  is a whole number. The sampling frequency for the bolometers and thermistors is in turn equal to the bias frequency divided by a whole number.

In order to achieve the necessary 20-bit sampling using a 16-bit ADC (the highest resolution available with space qualified devices), an offset subtraction scheme is implemented. The functions and characteristics of each element of the chain are described in the following sections.

### 3.3 Bolometer – JFET harness

The **bolometer** signals are fed to JFETs located outside the SPIRE Focal Plane Unit (FPU). The JFET input capacitance plus the stray capacitance of the harness between the **bolometer** and the JFET forms an  $RC$  filter with the parallel combination of the **bolometer** and the load resistance. This results in a some attenuation and phase change of the signal. Let the total capacitance (harness + JFET input capacitance) be  $C_H$ . The harness transfer function is represented as

$$H_H(\omega_b) = \frac{1}{1 + j\omega_b \tau_H}, \quad (5)$$

where

$$j = \sqrt{-1},$$

and

$$\tau_H = \left[ \frac{R_L R_d}{R_L + R_d} \right] C_H. \quad (6)$$

The magnitude of  $H_H(\omega_b)$  is  $|H_H(\omega_b)| = \frac{1}{[1 + (\omega_b \tau_H)^2]^{1/2}}$ .

The values of  $C_H$  currently adopted are 50 pF for the photometer **bolometers** and 20 pF for the spectrometer **bolometers**. For  $R_L = 20 \text{ M}\Omega$ ,  $R_d = 3 \text{ M}\Omega$ , and  $\omega_b = 2\pi(130) \text{ rad s}^{-1}$ , the corresponding value of  $|H_H(\omega_b)|$ , is 0.994 with a phase of about  $6^\circ$ .

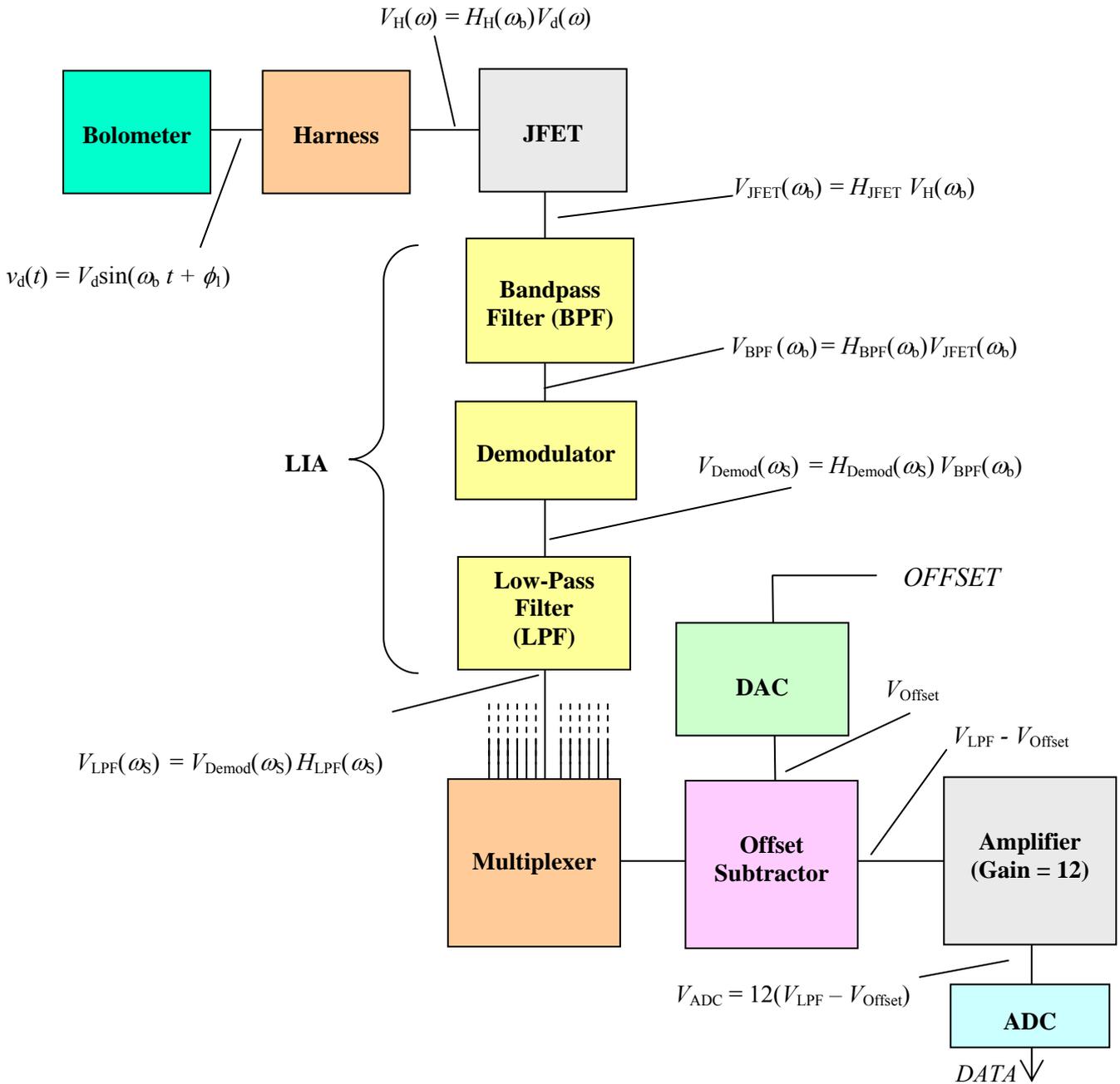


Figure 2: SPIRE bolometer signal chain.

### 3.4 JFETs

The output of the JFET source followers reproduce their input voltages, with a small attenuation, and – importantly – with a much lower output impedance than the **bolometer**. This allows the next stage of amplification to be located in the warm electronics (on the Herschel Service Module) with negligible attenuation due to capacitance of the several metres of cable in between.

The JFETs have a transfer function,  $H_{\text{JFET}}$ , which we take to be uniform over the range of bias frequencies used in SPIRE. The magnitude of  $H_{\text{JFET}}$  is slightly less than unity, and we also assume that it is the same for both JFETs in that pair. Currently, a representative value of  $H_{\text{JFET}} = 0.96$  is adopted for all JFETs. It is planned to measure  $H_{\text{JFET}}$  explicitly for each channel, and a calibration table of gains will be produced.

The RMS voltage at the JFET output is

$$V_{\text{JFET-RMS}}(\omega_b) = |H_{\text{H}}(\omega_b)H_{\text{JFET}}|V_{\text{d-RMS}}. \quad (7)$$

### 3.5 Lock-in Amplifier

The signal from the JFETs is demodulated by the LIA, which has three stages:

- (i) a band-pass filter/amplifier to remove the DC component and amplify the signal;
- (ii) a square-wave synchronous demodulator which rectifies the signal;
- (iii) a low-pass filter which produces a low-frequency output proportional to  $V_{\text{d}}$ .

#### 3.5.1 Band-pass filter

The transfer function of the SPIRE bandpass filter is given by

$$H_{\text{BPF}}(\omega_b) = H_0 \left[ \frac{j\omega_b \tau_B}{1 + j\omega_b \tau_B + (j\omega_b)^2 \tau'_B \tau_B} \right], \quad (8)$$

where  $H_0 = 262.8$  for the photometer bolometers and 114.4 for the spectrometer bolometers,  $\tau_B = 4.7$  ms, and  $\tau'_B = 1.244 \times 10^{-4}$  s for the photometer and  $6.68 \times 10^{-5}$  s for the spectrometer (*DCU DD* p. 36; p. 49).

The magnitude of  $H_{\text{BPF}}$  as a function of bias frequency is plotted in Figure 3 for both the photometer and spectrometer. It is designed to be fairly flat across the range of bias that are expected to be used.

For the nominal photometer and spectrometer bias frequencies, we have:

Photometer ( $\omega_b = 130$  Hz):  $|H_{\text{BPF}}| = 259.61$ ;

Spectrometer ( $\omega_b = 160$  Hz):  $|H_{\text{BPF}}| = 113.18$ .

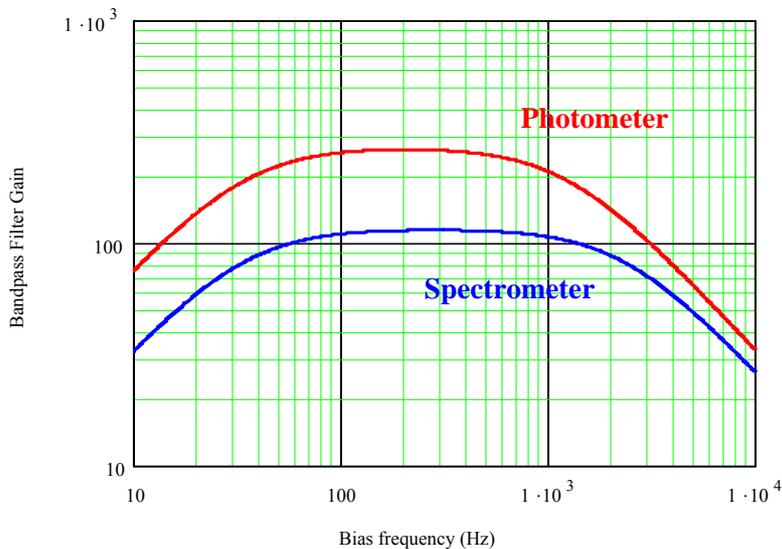


Figure 3: Magnitude of band-pass filter gain vs. bias frequency.

### 3.5.2 Square-wave demodulator

The demodulator multiplies the alternating input signal by a square wave reference voltage which is ideally in phase with the input signal, such that the multiplication factor is +1 during the positive half-cycle of the input and -1 during the negative half-cycle. It then functions as a perfect rectifier. Under these conditions, the DC or low-frequency component of the demodulator output is just the mean value of a rectified sine wave:  $(2/\pi)V_{\text{BPF}} = (0.637)V_{\text{BPF}}$ , where  $V_{\text{BPF}}$  is the amplitude of the input. But the output will be less than this if the phase of the reference is not perfectly matched to that of the input. The (frequency-independent) transfer function, as a function of phase difference  $\Delta\phi$ , is given by

$$H_{\text{Demod}}(\Delta\phi) = \left[ \frac{2}{\pi} \right] \cos(\Delta\phi), \quad (9)$$

which is plotted in Figure 4.

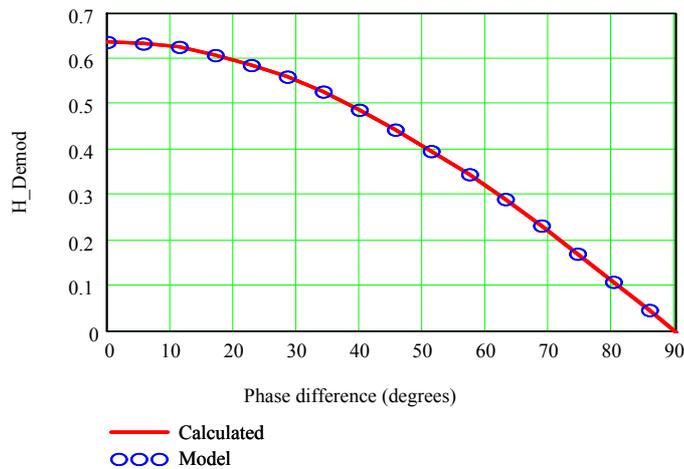


Figure 4: Demodulator gain vs. phase input difference. Red curve: gain as explicitly calculated by direct integration of the rectified waveform; blue dots:  $H_{\text{Demod}}$  as given by equation (9).

For the case of near zero  $\omega_s$  (slowly varying radiant power), the demodulator output is a DC voltage related to the amplitude of the JFET output voltage by

$$V_{\text{Demod}}(\omega_b, \phi) = H_{\text{BPF}}(\omega_b) H_{\text{Demod}}(\Delta\phi) V_{\text{JFET}} = \sqrt{2} H_{\text{BPF}}(\omega_b) H_{\text{Demod}}(\Delta\phi) V_{\text{JFET-RMS}} \quad (10)$$

If  $V_d$  is varying at angular frequency  $\omega_s$  ( $\ll \omega_b$ ) due to **bolometer** radiant power modulation, then  $V_{\text{Demod}}$  will also vary accordingly.

The phase difference is dictated largely by the bolometer-JFET harness time constant,  $\tau_H$ . In setting up the LIAs, the phase of the LIA reference can be adjusted for each array, so as to correct for the phase difference  $\phi_1$  in equation (2) and hence make  $\Delta\phi$  equal to zero. In flight, it will be adjusted, **ideally** to make  $\Delta\phi = 0$  for the nominal operating condition (telescope background; pointing at blank sky); **but there** will be a slight degree of non-optimal phase due to the spread in **bolometer** impedances across the array. Furthermore, since the **bolometer** impedance varies with radiant loading, a component of phase mismatch will also arise when looking at bright sources.

In setting the phase, the bias phase is changed iteratively in order to maximise either the signal from a selected bolometer channel or the modal maximum signal across the array. Let  $\phi_{\text{fix}}$  be the resulting value of the phase set for a given array (either for a selected channel or the mean of all the channels). Due to the spread in resistance values of the bolometers, there will be a small initial phase offset for each bolometer with respect to  $\phi_{\text{fix}}$ :

$$\phi_{d-\text{nom}} = \phi_{\text{fix}} + \Delta\phi_{d-\text{nom}}. \quad (11)$$

$\Delta\phi_{d-\text{nom}}$  corresponds to the resistance of the bolometer when viewing blank sky. If the bolometer resistance changes significantly from  $R_{d-\text{nom}}$  to  $R_d$  (due for instance to a strong signal power), then the phase offset will change to a new value:

$$\Delta\phi_d = \Delta\phi_{d-\text{nom}} + \left[ \tan^{-1}(\omega_b \tau_{H-\text{nom}}) - \tan^{-1}(\omega_b \tau_H) \right]. \quad (12)$$

These phase differences will be small, and, as can be seen from Figure 4, the effect on the demodulator transfer function is also small. Nevertheless, it can be taken into account in the procedure for calculating the bolometer resistance (see Section 3.9).

### 3.5.3 Low-pass filter (LPF)

The low pass filter following the demodulator is designed to reject all higher-frequency components from the demodulator output, passing just the DC or slowly varying voltage directly proportional to the amplitude of the bolometer voltage. If the radiant signal on the bolometer is constant, then it will be just a DC component. If the radiation is modulated at angular frequency  $\omega_s$  (within the filter passband) then there will be a corresponding LPF output at angular frequency  $\omega_s$ .

For the photometer, the low-pass filters are implemented as 4-pole Bessel filters, with transfer function given by (DCU DD p.40):

$$H_{\text{LPF-P}}(\omega_s) = \left[ \frac{1.93}{1 + j\omega_s(42.6 \times 10^{-3}) + (j\omega_s)^2(5 \times 10^{-4})} \right] \left[ \frac{1}{1 + j\omega_s(25 \times 10^{-3}) + (j\omega_s)^2(4 \times 10^{-4})} \right] \times \left[ \frac{1}{1 + j\omega_s(10^{-3})} \right]. \quad (13)$$

and for the spectrometer, 6-pole Bessel filters are used, with transfer function given by (DCU DD p.53):

$$H_{\text{LPF-S}}(\omega_s) = \left[ \frac{2.86}{1 + j\omega_s(7.85 \times 10^{-3}) + (j\omega_s)^2(1.6 \times 10^{-5})} \right] \left[ \frac{1}{1 + j\omega_s(3.25 \times 10^{-3}) + (j\omega_s)^2(1.09 \times 10^{-5})} \right] \times \left[ \frac{1}{1 + j\omega_s(6.26 \times 10^{-3}) + (j\omega_s)^2(1.47 \times 10^{-5})} \right] \left[ \frac{1}{1 + j\omega_s(10^{-4})} \right]. \quad (14)$$

The magnitudes of these are plotted vs. bolometer modulation angular frequency ( $\omega_s$ ) in Figure 5 on linear and logarithmic scales.

For a bolometer channel with low  $\omega_s$  (no or very slow modulation of the radiant power), the DC gain of the LPF applies:

$$|H_{\text{LPF-P}}(0)| = 1.93 \quad \text{for the photometer,}$$

and

$$|H_{\text{LPF-S}}(0)| = 2.86 \quad \text{for the spectrometer.}$$

The overall gain of the LIA chain, relating LPF DC output voltage to the RMS JFET output voltage is given by

$$G_{LIA}(\omega_b) = \frac{V_{LPF}}{V_{JFET-RMS}} = \sqrt{2} H_{Demod}(\Delta\phi) |H_{BPF}(\omega_b)| |H_{LPF}(0)| . \quad (15)$$

For perfect phasing of the demodulator, ( $\Delta\phi = 0$ ) we have

$$G_{LIA}(\omega_b) = (0.9003) |H_{BPF}(\omega_b)| |H_{LPF}(0)| . \quad (16)$$

This overall gain is plotted against bias modulation frequency in Figure 6.

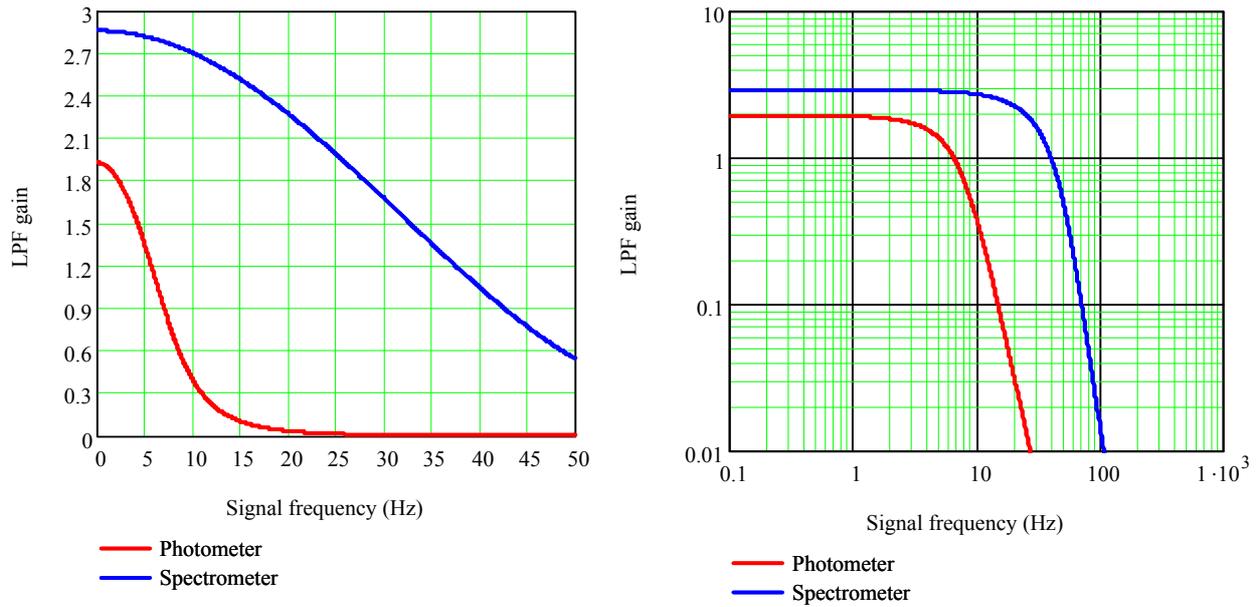


Figure 5: Low-pass filter gains as a function of bolometer signal frequency.

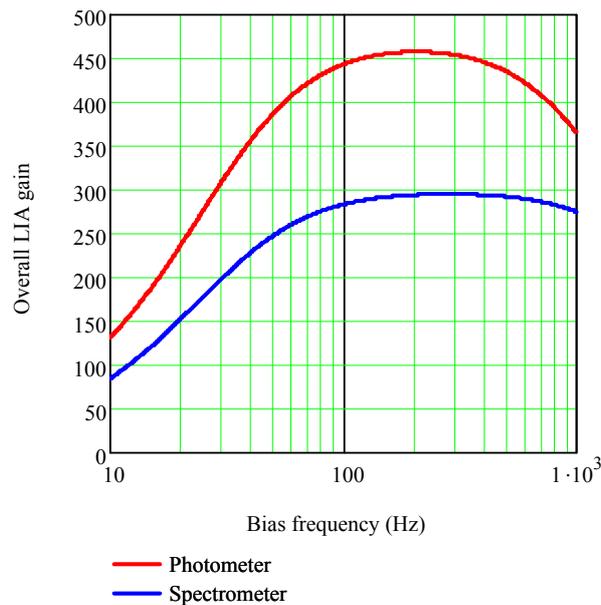


Figure 6: Overall gain of LIA signal chain, relating LPF DC output to the RMS voltage at the JFET output.

For example, taking our nominal bias frequencies of 130 Hz (photometer) and 160 Hz (spectrometer), we have:

$$\begin{aligned} \text{Photometer:} \quad G_{\text{LIA}} &= (259.61)(1.93)(0.9003) &= 451.1 & \text{(see DCU DD p. 44);} \\ \text{Spectrometer:} \quad G_{\text{LIA}} &= (113.18)(2.86)(0.9003) &= 291.4 & \text{(see DCU DD p. 57).} \end{aligned}$$

### 3.6 Multiplexer

The LIA outputs are multiplexed in groups of 16 (photometer) or 12 (spectrometer). In the case of the photometer, a second stage of multiplexing combines three groups of 16 to form a group of 48 channels.

### 3.7 Offset subtraction and the calculation of JFET voltage from telemetry data

After multiplexing, a pre-determined offset is subtracted for each channel. Offset subtraction is needed because the signals need to be sampled with greater precision than the 16 bits available from the ADC. This is achieved by subtracting a suitable DC offset from each signal and adding in an additional gain stage before digitisation. The offset voltage is generated by the DCU from a 4-bit DAC with binary input value *OFFSET* (range = 0 – 15).

At the start of each observation, the value of *OFFSET* is set for each bolometer individually by the DRCU according to a procedure described in Section 3.8 below. It is not possible to change the offsets during an observation, so the settings must be able to cope with the entire range of bolometer power expected during the observation – this includes changes due to the astronomical signal (all observing modes) and due to signal offsets created by chopping (point source and jiggle-map modes).

After offset subtraction, the signal is amplified by a gain of 12 and then digitised, producing a binary output value *DATA*, with range 0 to ( $2^{16} - 1$ ), which is sent to the DPU for telemetry.

The total gain of the DCU chain is thus  $G_{\text{tot}}(\omega_b) = 12G_{\text{LIA}}(\omega_b)$ . For the nominal bias frequencies used above, we therefore have

$$\begin{aligned} \text{Photometer:} \quad G_{\text{tot}} &= (12)(451.1) &= 5413 & \text{(see DCU DD p. 77);} \\ \text{Spectrometer:} \quad G_{\text{tot}} &= (12)(291.4) &= 3497 & \text{(see DCU DD p. 77).} \end{aligned}$$

For bias frequency  $\omega_b$ , the RMS voltage at the BPF input (i.e., the JFET output) is related to the digital ADC output, *DATA*, and the offset level, *OFFSET*, by the following formula (DCU DD p. 77):

$$V_{\text{JFET-RMS}}(\omega_b, \text{DATA}, \text{OFFSET}) = \left[ \frac{5}{G_{\text{tot}}(\omega_b)} \right] \left[ \frac{\text{DATA} - 2^{14} + (52428.8)(\text{OFFSET})}{(2^{16} - 1)} \right]. \quad (17)$$

This voltage is in turn related to the RMS bolometer voltage by

$$V_{\text{JFET-RMS}}(\omega_b) = H_{\text{H}}(\omega_b) H_{\text{JFET}} V_{\text{d-RMS}}. \quad (18)$$

To see how the RMS voltage at the JFET output is related to the ADC output (*DATA*) and the value of *OFFSET*,  $V_{\text{JFET-RMS}}$  is plotted in Figure 7 for the case of the nominal photometer gain,  $G_{\text{tot}} = 5413$  (note that the numbers given in the DCU DD p. 77 correspond to the maximum gain of 5481). For  $G_{\text{tot}} = 5413$ , the full ADC range for each offset step is 0.92371 mV and the 15 available offset levels cover a range up to 11.824 mV, with some overlap between successive offset levels, as indicated in Table 1.

There are  $2^{16} - 1 = 65535$  ADC bits potentially available within each *OFFSET* range, so the voltage step corresponding to one bit is

$$\Delta V_{\text{JFET-RMS}}(1 \text{ bit}) = (0.92371 \text{ mV}) / (65535) = 14.09 \text{ nV}. \quad (19)$$

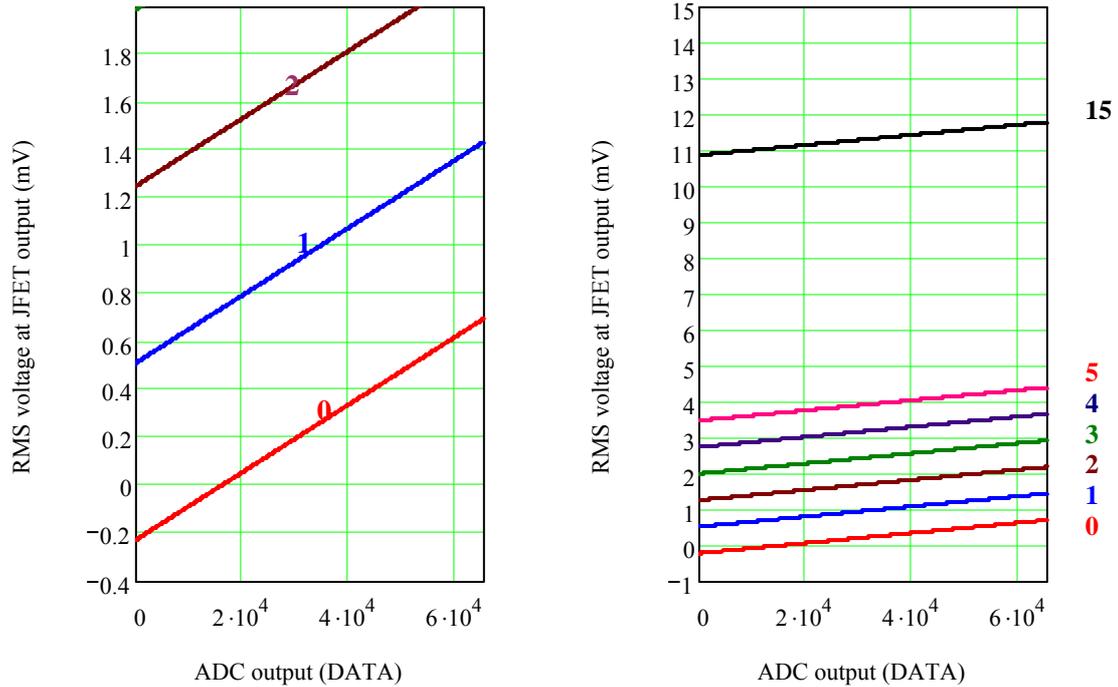


Figure 7: Photometer ADC output vs. JFET RMS output voltage for various values of *OFFSET* (for  $G_{\text{tot}} = 5413$ ).

Offset =	Lower limit (mV)	Upper limit (mV)
0	-0.23093	0.69277
1	0.50804	1.43175
2	1.24702	2.17072
3	1.98599	2.90969
4	2.72496	3.64867
5	3.46394	4.38764
6	4.20291	5.12661
7	4.94188	5.86558
8	5.68086	6.60456
9	6.41983	7.34353
10	7.15880	8.08250
11	7.89777	8.82148
12	8.63675	9.56045
13	9.37572	10.29942
14	10.11469	11.03840
15	10.85367	11.77737

Table 1:  $V_{\text{JFET-RMS}}$  range covered by each *OFFSET* value for the photometer with  $G_{\text{tot}} = 5413$ .

### 3.8 Offset setting procedure

Before each observation, the offsets are set for all **bolometers** according to the procedure shown in Figure 8. Note that this procedure is the one actually implemented in the DRCU, and is different to the one described in the *DCU DD* (p. 126).

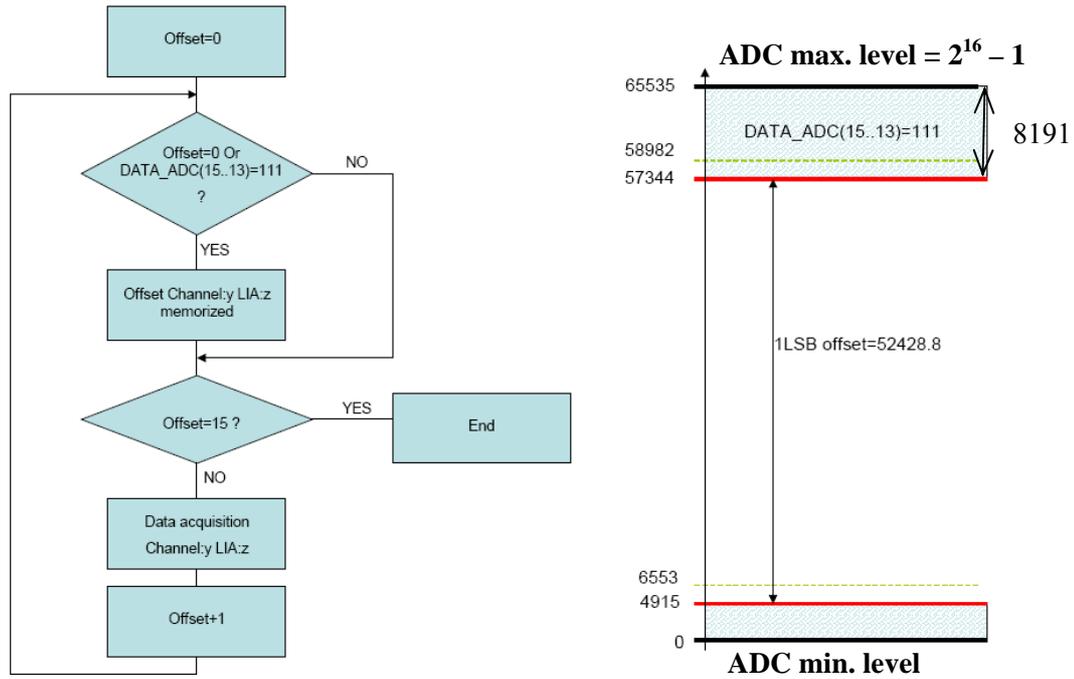


Figure 8: Procedure for setting the value of *OFFSET* and range of ADC output values corresponding to one offset setting.

For a given value of  $V_{\text{JFET-RMS}}$  at the start of the observation:

1. *DATA* is a 16-bit number with range 0 to  $2^{16} - 1$ , with the bits numbered 0 – 15.
2. The 4-bit *OFFSET* is first set to 0000.
3. *OFFSET* is then incremented until the three most significant bits of *DATA* are not 111 (i.e.  $DATA < 57344$ ) or *OFFSET* is 15.
4. At the end of this procedure, *DATA* has a value between 57344 and 4915.

This procedure is completely deterministic in that a given value of  $V_{\text{JFET-RMS}}$  will result in a particular value of *OFFSET* being selected. Table 2 lists the selected *OFFSET* values as a function of  $V_{\text{JFET-RMS}}$  for the case of the photometer with  $G_{\text{tot}} = 5413$ , and the chosen *OFFSET* is plotted against  $V_{\text{JFET-RMS}}$  in Figure 9. The actual voltage range per level (i.e., upper – lower voltage for a given selected offset is 0.73898 V).

Note that when  $V_{\text{JFET-RMS}}$  is just above an offset threshold, the value of *DATA* is 4915, and when it is just below an offset threshold, *DATA* is at its maximum allowed value (before changing the offset) of 57343.

If the voltage decreases during the observation (as will usually happen if the offsets are set off-source), then in the worst instance, the available dynamic range is 4915 bits. If the voltage decreases during the observation, the worst case dynamic range is 8191 bits.

To illustrate this, consider first the case of  $V_{\text{JFET-RMS}} = 1.316296$  mV (Table 2):

- This is just large enough to make *OFFSET* = 2, and the corresponding value of *DATA* = 4915
- For *OFFSET* = 2, the ADC zero level corresponds to  $V_{\text{JFET-RMS}} = 1.2470170$  mV (Table 1).
- The corresponding dynamic range is  $1.316296 - 1.2470170 = 0.069279$  mV.
- The same “worst case” dynamic range applies to all offset settings.

Now consider the case of  $V_{\text{JFET-RMS}} = 1.316295$  mV (Table 2)

- This is the highest value that will make *OFFSET* = 1, and the corresponding value of *DATA* = 57344.

- For  $OFFSET = 1$ , the ADC zero level corresponds to  $V_{JFET-RMS} = 0.508044$  mV (Table 1).
- The corresponding dynamic range is  $1.316295 - 0.508044 = 0.808251$  mV.
- The same “best case” dynamic range applies to all offset settings.

Offset	Voltage range (mV) for which this offset is chosen	ADC zero level for this offset	ADC max. level for this offset	G = 5413		
$o =$	$vL_o =$	$vU_o =$	$V_{JFETrms}(0, Offset, G) = V_{JFETrms}(2^{16} - 1, Offset, G)$	$= DATA(vL_j, j, G)$	$= DATA(vU_j, j, G)$	
0	-0.16165	0.577323	-0.230929	0.69277	4915	57344
1	0.57732	1.316296	0.508044	1.43175	4915	57344
2	1.31629	2.055269	1.247017	2.17072	4915	57344
3	2.05527	2.794242	1.985990	2.90969	4915	57344
4	2.79424	3.533215	2.724963	3.64867	4915	57344
5	3.53321	4.272188	3.463936	4.38764	4915	57344
6	4.27219	5.011161	4.202909	5.12661	4915	57344
7	5.01116	5.750134	4.941882	5.86558	4915	57344
8	5.75013	6.489107	5.680855	6.60456	4915	57344
9	6.48910	7.228080	6.419828	7.34353	4915	57344
10	7.22808	7.967053	7.158801	8.08250	4915	57344
11	7.96705	8.706026	7.897774	8.82148	4915	57344
12	8.70602	9.444999	8.636747	9.56045	4915	57344
13	9.44500	10.183972	9.375720	10.29942	4915	57344
14	10.18397	10.922945	10.114693	11.03840	4915	57344
15	10.92294	11.661918	10.853666	11.77737	4915	57344

Table 2: Offset values and the ranges of  $V_{JFET-RMS}$  for which they are selected (photometer with  $G_{tot} = 5413$ ).

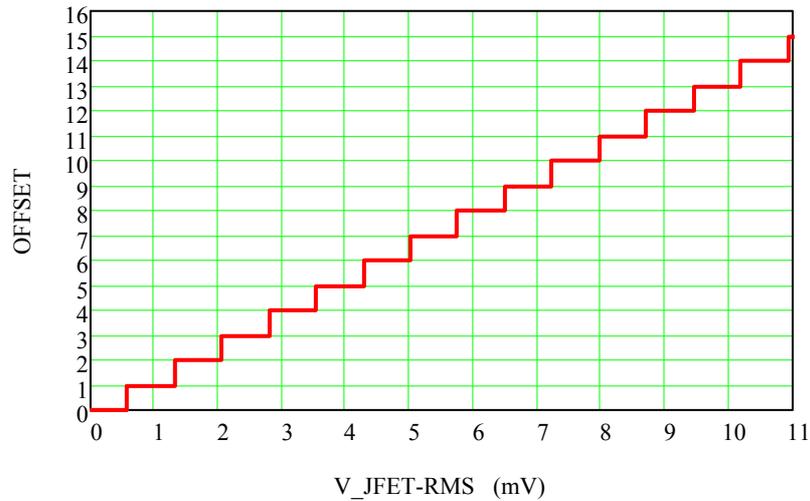


Figure 9: Selected  $OFFSET$  vs.  $V_{JFET-RMS}$  (photometer with  $G_{tot} = 5413$ ).

### 3.8.1 Offset setting for the photometer

Consider an observation during which the in-beam flux density will vary between  $S_{v-min}$  and  $S_{v-max}$ . Before the observation, the  $OFFSET$  value will be set up for each **bolometer**, determined by its output voltage. Offsets can be set either off-source (default for the photometer) or on-source.

**Off-source case:** the nominal situation is that  $S_v = S_{v-min} = 0$ , so that  $V_{JFET-RMS} = V_o$  at the telescope position for which the offsets are set. While the observations are in progress, the bolometer output voltage is always less than the value when the offset is selected -  $V_{JFET-RMS}$  moves towards the zero level of the ADC, with a maximum change  $\Delta V$ , as shown in Figure 10. The worst case dynamic range corresponds to the case in which the  $V_o$  is just above an offset threshold, so that  $DATA = 4915$  and the difference between it and the value that will give  $DATA = 0$  is at its smallest: the allowed drop in **bolometer** voltage during the observation is therefore at its smallest.

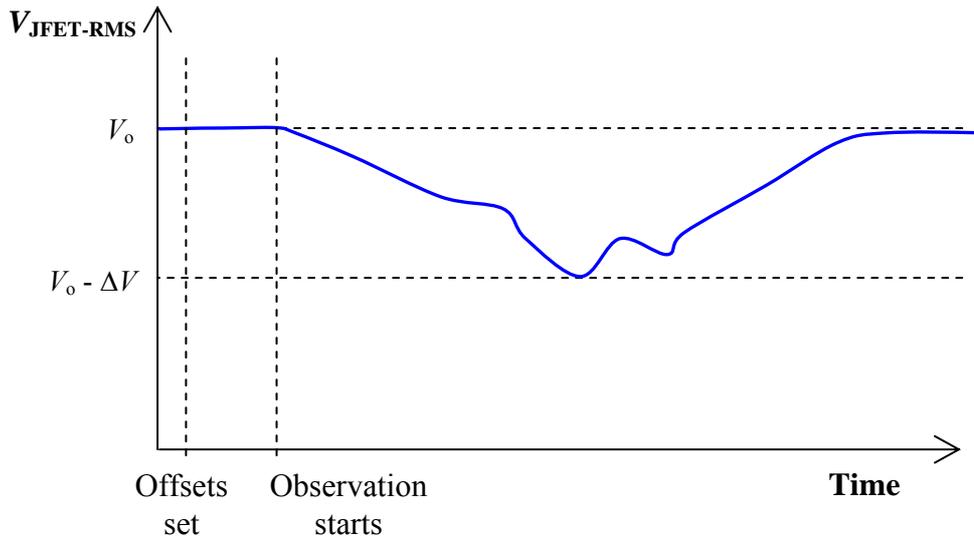


Figure 10: Example signal voltage timeline with offsets set at zero signal before the observation.

The worst case dynamic range is  $4915 \times \Delta V_{\text{JFET-RMS}}(1 \text{ bit}) = (4915)(14.09 \text{ nV}) = 0.06928 \text{ mV}$ .

The best case dynamic range corresponds to the case in which the  $V_{\text{JFET-RMS}}$  is just below an offset threshold, so that  $DATA = 57344$  and the difference between it and the value that will give  $DATA = 0$  is at its largest: the allowed drop in **bolometer** voltage during the observation is therefore at its largest.

The best case dynamic range is  $57344 \times \Delta V_{\text{JFET-RMS}}(1 \text{ bit}) = (57344)(14.09 \text{ nV}) = 0.80825 \text{ mV}$ .

To get a rough estimate of the corresponding source brightness limits, the SPIRE photometer sensitivity model (assuming 20 mV RMS bias voltage for all arrays) has been used to derive the following information:

Band	Total background power (mainly from the telescope) (pW)	Astronomical gain (Jy pW <sup>-1</sup> )	Responsivity (MV W <sup>-1</sup> )	Worst case dyn. range of 0.06928 mV expressed in pW	Worst case dynamic range in Jy
PSW	1.7	137	320	0.217	(0.217)*137 = 30
PMW	1.0	250	330	0.211	(0.211)*250 = 53
PLW	1.2	226	350	0.199	(0.199)*226 = 45

So the worst case dynamic range corresponds to between about 30 and 50 Jy. The best case limits are about 12 times larger, so objects brighter than several hundred Jy will pose problems with saturation unless the **bolometer** bias is adjusted.

**General case:** Let the offsets be set at a position for which the flux density is some fraction  $h$  of the total range – i.e.,  $S_v = h(S_{v-\text{max}} - S_{v-\text{min}})$ . The value of  $h$  can be different for each **bolometer** as they view different parts of the sky.  $V_{\text{JFET-RMS}}$  can now increase or decrease during the observations, as shown in Figure 11.

In this case, the offsets are set at  $V_{\text{JFET-RMS}} = V_o - h(\Delta V)$ . The dynamic range requirement for increasing sky signal (decreasing output voltage) is now less than before, which is good. However, during parts of the observation, the voltage will also be higher than the initial value, by an amount up to  $h(\Delta V)$ . In the worst case, the available dynamic range for this is 8191 bits.

Since the dynamic range at the top of the ADC is better than at the bottom, it is better in principle to set the offsets on-source. However, since most photometer observations involve mapping and the position of peak brightness will not necessarily be known or easily identified, the default will be to set the offsets off-source (so that,  $V_{\text{JFET-RMS}}$  only decreases during the observation).

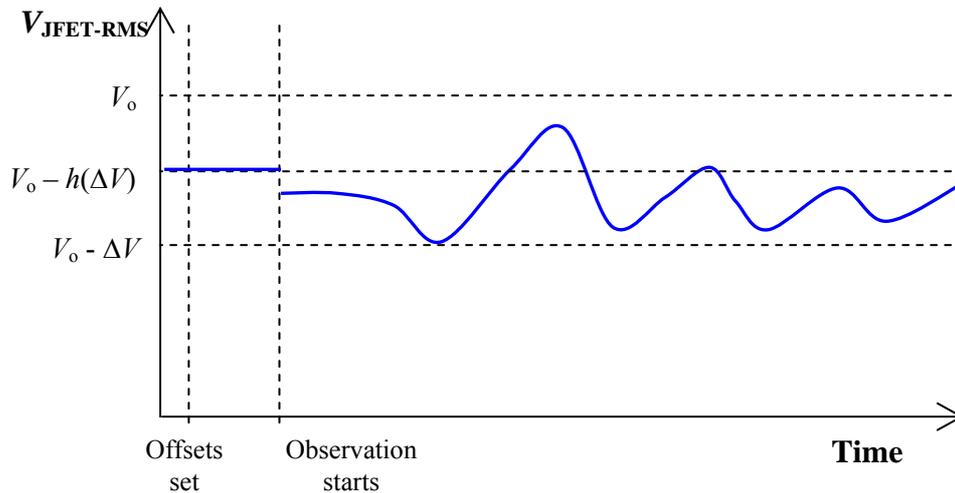


Figure 11: Example signal timeline with offsets set at an intermediate signal level before the observation.

### 3.8.2 Offset setting for the FTS

Assume for simplicity that the telescope is perfectly nulled by SCal (in practice there will be a small imbalance). Under that condition, an observation of blank sky results in a null interferogram – the power absorbed by the **bolometer** is constant throughout the interferogram at  $(1/2)(Q_{\text{Tel}} + Q_{\text{SCal}}) = Q_{\text{Tel}}$ , and the corresponding output voltage is constant at  $V_0$ . Now let a source be observed which results in an increase  $\Delta Q$  in the broadband continuum power coming through the telescope. This will be split equally between the output ports, increasing the continuum power absorbed by the **bolometers**. The unmodulated output voltage (corresponding to the DC level in the wings of the interferogram) will thus decrease by some corresponding – let this be  $\Delta V/2$  (corresponding to  $\Delta Q/2$ ).

When the mirror is scanned, the resulting interferogram represents the difference between the telescope and SCal input ports. One output port will correspond to (Telescope + Sky) – SCal, and the other to SCal – (Telescope + Sky). In the former case, the interferogram will have a negative-going central maximum (more radiant power), and in the latter case a positive-going central maximum (less radiant power). The peak height of the interferogram is equivalent to the continuum level, and so is also  $\Delta V/2$ . The two possible interferograms are illustrated in Figure 12. The total dynamic range that must be available to be able to cope with either case is  $V_0$  to  $V_0 - \Delta V$ .

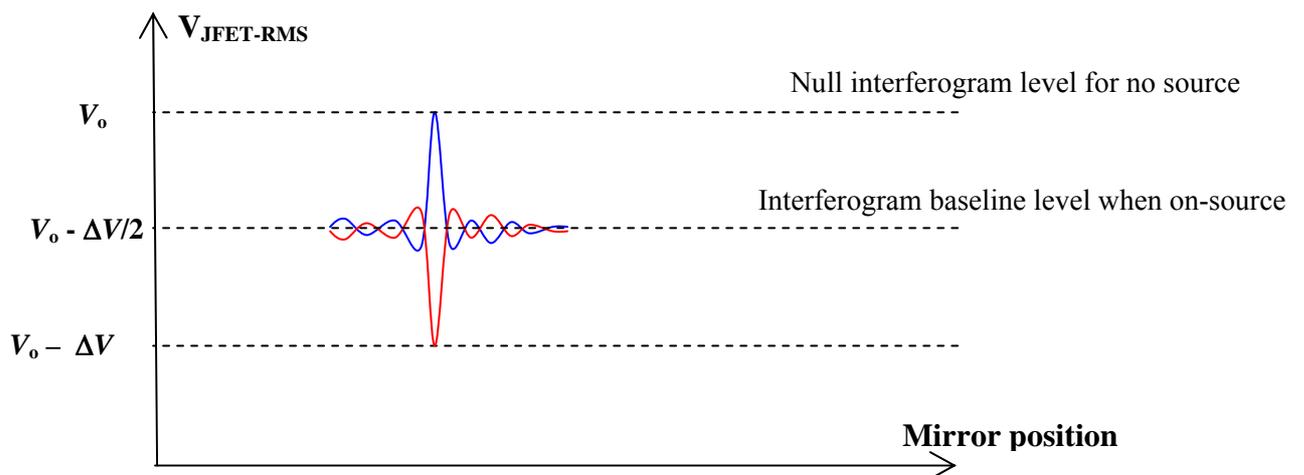


Figure 12: Interferogram dynamic range, assuming perfect telescope nulling. The output voltage is  $V_0$  for no source, and  $(V_0 - \Delta V/2)$  off ZPD when on source. The red interferogram is for the port corresponding to (Telescope + Sky) – SCal, and the blue is for the port corresponding to SCal – (Telescope + Sky).

**Offsets set off-source (i.e., at  $V_o$ ):** The output voltage will always decrease. When the telescope is pointed on-source, the interferogram baseline level will be  $V_o - \Delta V/2$ , and we must be able to cope with a change of  $\pm \Delta V/2$  about that level. In the worst case, with the offset set initially at the bottom of its range, the highest continuum level that can be coped with corresponds to  $(4915)/2 = 2458$  bits.

**Offsets set on-source (i.e., at  $V_o - \Delta V/2$ ):** The output voltage can now go up or down in the interferogram. If the offset is set at the bottom of the range, the output can go down by 4915 bits. If it is set at the top, the output can go up by 8192 bits.

So setting the offsets on-source has an advantage in terms of the worst-case dynamic range.

### 3.9 Measurement of **bolometer** voltage and resistance

From equation (17), the RMS voltage at the JFET output can be computed from the telemetry data value. This can be used to derive the **bolometer** voltage, current and resistance by an iterative procedure designed to take into account the  $RC$  roll-off due to the harness transfer function (equations 5 and 6) and also any changes in the phasing of the demodulator.

**Step 1:** Estimate  $V_{d-RMS}$  and  $R_d$ , taking  $H_H(\omega_b) = 1$  :

$$V_{d-RMS} = \frac{V_{JFET-RMS}}{H_{JFET}}, \quad I_{b-RMS} = \frac{V_{b-RMS} - V_{d-RMS}}{R_L}, \quad \text{and} \quad R_d = \frac{V_{b-RMS}}{I_{b-RMS}} - R_L. \quad (20)$$

**Step 2:** Estimate  $H_H(\omega_b)$  and  $\Delta\phi_d$ :

$$|H_H(\omega_b)| = \frac{1}{[1 + (\omega_b \tau_H)^2]^{1/2}} \quad \text{with} \quad \tau_H = \left[ \frac{R_L R_d}{R_L + R_d} \right] C_H, \quad (21)$$

and  $\Delta\phi_d$  given by equation (12) in Section 3.5.2:  $\Delta\phi_d = \Delta\phi_{d-nom} + [\tan^{-1}(\omega_b \tau_{H-nom}) - \tan^{-1}(\omega_b \tau_H)]$ .

Note: The manner in which the small variations in LIA phase from detector to detector is to be handled is still under review. The scheme presented here should be taken as the baseline for now.

**Step 3:** Recalculate  $V_{d-RMS}$  and  $R_d$ :

$$V_{d-rms} = \frac{V_{JFET-RMS}}{H_{JFET} |H_H(\omega_b)| \cos(\Delta\phi_d)}, \quad I_{b-rms} = \frac{V_{b-rms} - V_{d-rms}}{R_L}, \quad \text{and} \quad R_d = \frac{V_{b-RMS}}{I_{b-RMS}} - R_L. \quad (22)$$

Continue iterating (repeat steps 2 and 3) until  $I_{b-RMS}$  and  $R_d$  converge (criterion: change on iteration  $< 0.1\%$ ).

The RMS **bolometer** voltage is then just  $V_{d-RMS} = I_{b-RMS} R_d$ . (23)

The timelines of voltage and **resistance** constitute the Level 0.5 Photometer Data Timeline (PDT) and Spectrometer Detector Timeline (SDT) products.

#### 4. Photometer system transient response

The overall response of the system depends on the transient response characteristics of the **bolometer** and the low-pass filter. There is evidence from measurements on similar **bolometers** (used on Planck-HFI, BLAST, and BICEP) that SPIRE-like bolometers may not exhibit a pure first-order response (characterised by a single time constant), but may also have a low-level slow response. Here we assume a variation of **bolometer** responsivity with frequency of the following form:

$$H_{\text{Bol}}(\omega_s) = \frac{1-a}{1+j\omega_s\tau_1} + \frac{a}{1+j\omega_s\tau_2}. \quad (24)$$

Typically, the primary time constant,  $\tau_1$ , is about 6 ms for the photometer **bolometers** and slightly lower for the FTS **bolometers**. The “slow response” time constant,  $\tau_2$ , can be several hundred ms, with the amplitude parameter  $a$  in the range 10 – 30%. The detailed slow-response characteristics of the SPIRE **bolometers** have not been measured on the ground, so they will need to be measured during PV-phase through dedicated observations involving scanning point sources at various speeds.

##### 4.1 Transient response in chopped photometry mode

The overall response to the astronomical power incident on the **bolometer** is determined by the transfer function given in equation (24) followed by that of the electronics chain. First, we assume no slow response component, and  $\tau_1 = 6$  ms. The overall response of the system in chopped photometry mode depends on the waveform of the astronomical signal and the transient response of the **bolometer** and the low-pass filter. The astronomical signal timeline is not a pure step function because of the BSM settling time. The BSM movement between the two chop positions is quite fast, typically about 10 ms to get within 2”. For simplicity, we assume a point source observation with a chop throw of 163”, and a linear relationship between position and time along the trajectory, corresponding to a BSM slew rate of  $1.63 \times 10^4$  “/s. For a Gaussian beam of FWHM 24” (PMW), the corresponding timeline of astronomical power on the **bolometer** is as shown in Figure 13. The signal only begins to increase towards the end of the movement as the beam moves onto the source.

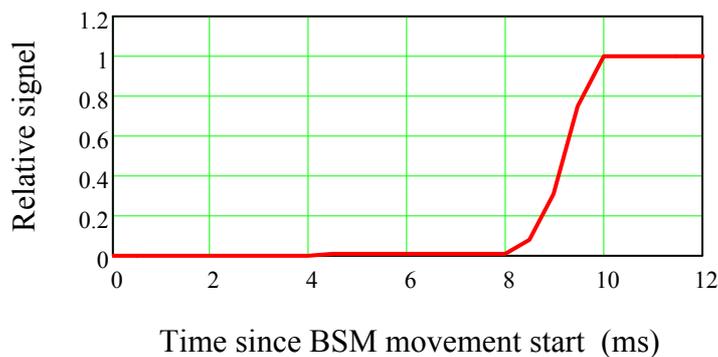


Figure 13: Simplified astronomical signal timeline for a PMW **bolometer** for a BSM movement starting at  $t = 0$ .

The normalised response of the overall system to this input is shown in Figure 14. The low-pass filter dominates the shape of the transient, and causes the significant phase delay between the BSM movement and the signal waveform.

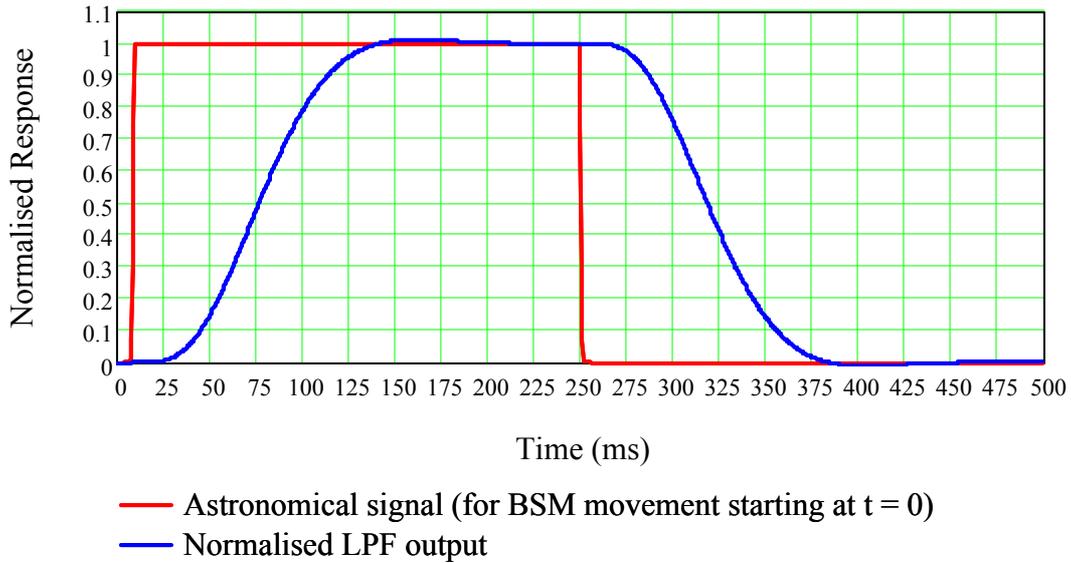


Figure 14: Overall transient response for BSM movements at  $t = 0$  and  $t = 250$  ms (corresponding to 2-Hz chop frequency). A pure first-order bolometer response is assumed (i.e.,  $a = 0$ ).

Figure 15 shows the overall response for the case of  $a = 0.2$  and  $\tau_2 = 0.5$  s. We see a reduced amplitude, since the slow component is mostly chopped out. However, it does impose a slope on the flat part of the waveform; and for the single chop cycle shown here, the system has not yet settled down.

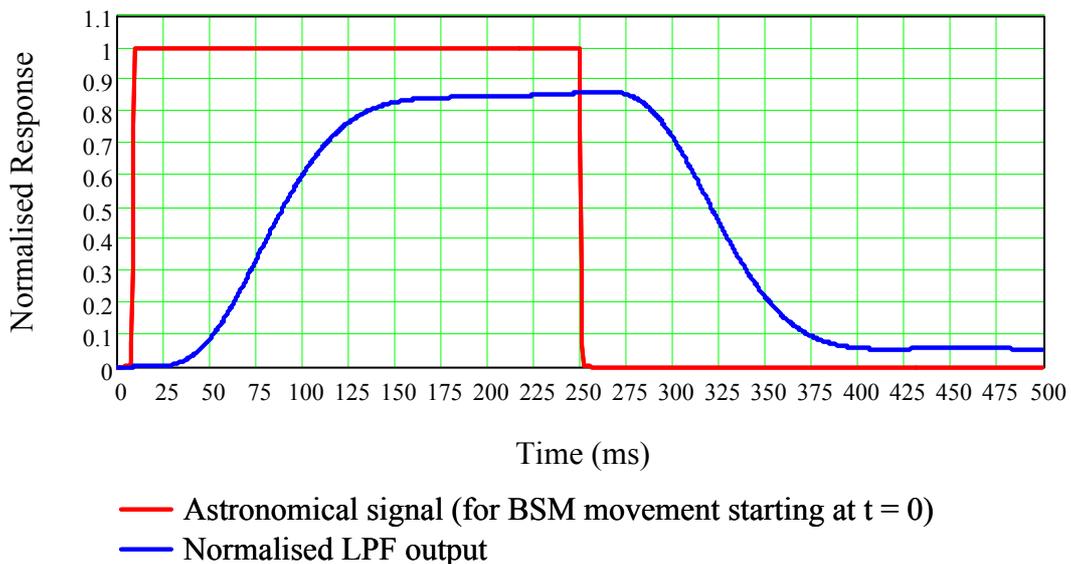


Figure 15: Overall transient response for BSM movements at  $t = 0$  and  $t = 250$  ms (i.e., 2-Hz chop frequency). A 20% slow bolometer response is assumed (i.e.,  $a = 0.2$ ), with a slow time constant of 0.5 sec.

#### 4.2 Transient response in scan-map mode

**Case of pure first-order bolometer response:** First, we consider the case if a pure first-order bolometer response ( $a = 0$ ). Spatial frequencies on the sky are encoded as electrical frequencies in the bolometer output in a manner that depends on the beam size and the telescope scan speed. For the fastest Herschel scan speed of  $60'' \text{ s}^{-1}$  and the smallest SPIRE beam FWHM of  $18''$  (for PSW), the beam crossing time is  $18/60 \text{ s} = 300$  ms. The LPF has a 3-dB frequency of approximately 5 Hz, corresponding to a time constant of

approximately 30 ms. The basic **bolometer** time constant is typically 6 ms, so the filter would be the dominant effect, and with a time constant  $\sim$  ten times faster than the beam crossing time, the distortion is small.

Figure 16 shows the system response to a Gaussian astronomical signal, corresponding to a scan across a point source at  $250\ \mu\text{m}$  ( $18''$  FWHM) at  $60''\ \text{s}^{-1}$ , with  $\tau_1 = 6\ \text{ms}$ . This is the worst case for SPIRE. The system response (black curve) is delayed by 74 ms and slightly attenuated (the delay will always be around this value, being dictated largely by the 5-Hz filter, with variations from one **bolometer** to another because of a spread of values of  $\tau_1$ ). For the nominal ( $30''\ \text{s}^{-1}$ ) and fast ( $60''\ \text{s}^{-1}$ ) scan rates, 74 ms corresponds to shifts in position of  $2.2''$  and  $4.4''$  respectively, which must be taken into account in the map-making process.

Figure 17 shows the residuals (delayed signal – system response) as a function of time during the scan. The signal loss at the peak is  $\sim 2\%$ . The loss is even smaller for the longer wavelength channels and for slower scan speed, as summarised in Table 3.

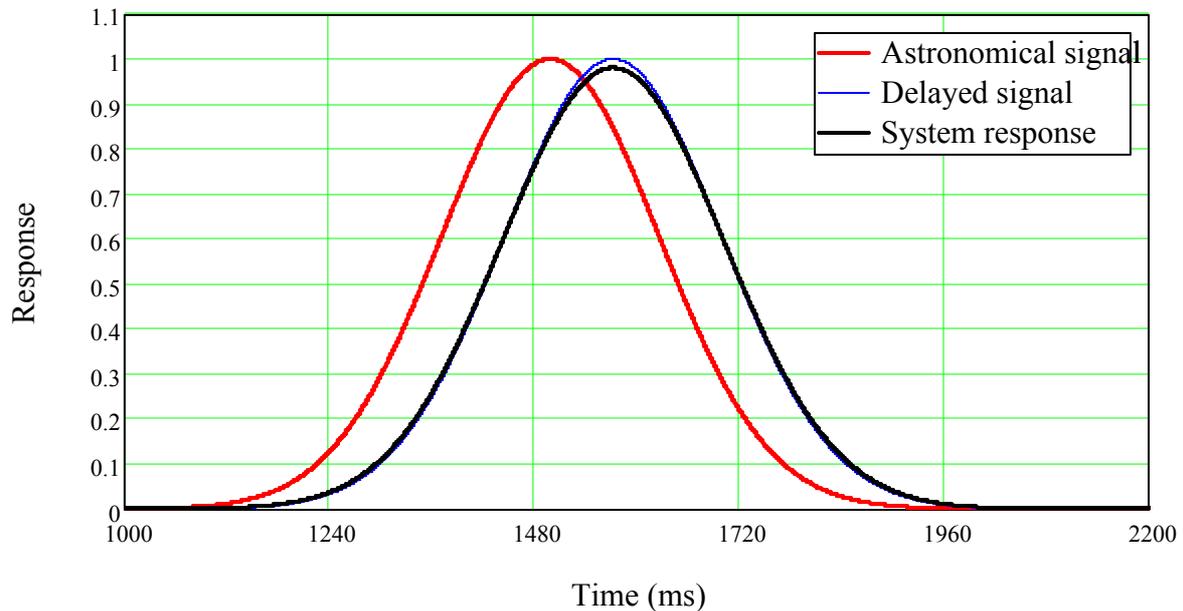


Figure 16: Signal chain response (black) to a Gaussian astronomical signal timeline (red) for a pure first-order **bolometer** response with  $\tau_1 = 6\ \text{ms}$ . The blue curve shows the signal timeline delayed by 74 ms.

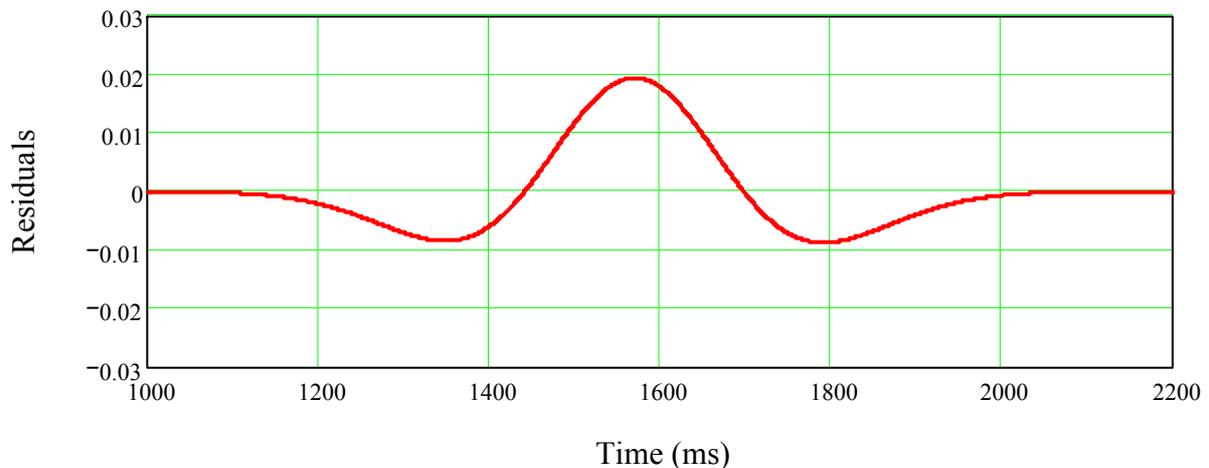


Figure 17: Difference between the delayed signal and the system response curves of Figure 16.

Scan speed ( $'' \text{ s}^{-1}$ )	Beam FWHM ( $''$ )	Peak loss (%)
30	18	0.5
	25	0.25
	36	0.12
60	18	1.9
	25	1.0
	36	0.5

Table 3: Percentage signal loss (with respect to a very slow scan) for scans across a point source in the three SPIRE bands, with scan rates of 30 and 60'' s<sup>-1</sup>.

**Case of bolometer response with slow component:** As an illustration of the impact of a slow component to the bolometer response, the example has been repeated but with  $a = 0.2$  and  $\tau_2 = 0.5$  s. Figure 18 shows system response to a the Gaussian astronomical signal for 18'' FWHM, 60'' s<sup>-1</sup> scan rate,  $\tau_1 = 6$  ms,  $\tau_2 = 0.5$  s,  $a = 0.2$ . The delay between the peaks is now about 80 ms and a loss of signal amplitude due to the reduction in the amplitude of the primary component. More significantly, there is also a long tail of response due to the slow component.

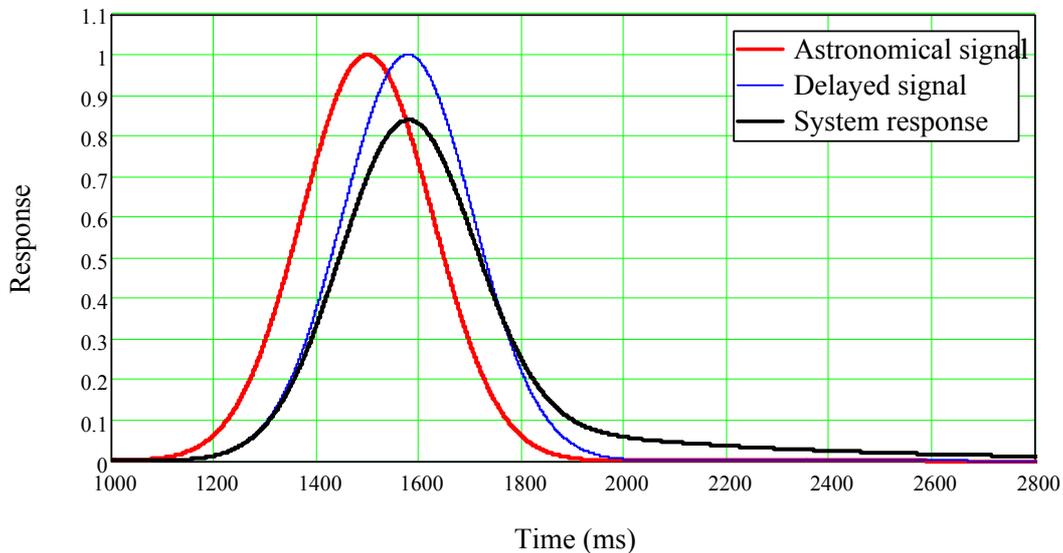


Figure 18: System response (black) to a Gaussian astronomical signal (red) for 18'' FWHM, 60'' s<sup>-1</sup> scan rate,  $\tau_1 = 6$  ms,  $\tau_2 = 0.5$  s,  $a = 0.2$ . The blue curve is the astronomical signal delayed by 80 ms.

### 4.3 Bolometer sampling in chopped photometry mode

For bolometer sampling in chopped photometry mode, the sequence of events is as follows:

1. At a given time  $t = 0$ , the BSM is commanded to move. No BSM sampling or bolometer sampling is occurring.
2. The BSM move command is immediately followed by a command to start the BSM sampling (in practice there is a delay of a few ms). The delay to the first sample is always fixed.
3. After a fixed delay of  $t_{\text{wait}}$  to allow the BSM to settle down at its new position, a series of  $n_{\text{samp}}$  bolometer samples at frequency  $f_{\text{samp}}$  is commanded.

Note:

- (i) The bolometer samples are automatically synchronised by the DCU electronics to the bias frequency  $f_b$ .
- (ii) There are short delays associated with commanding and sampling - these are ignored here: we assume that all detectors are sampled in a quasi-simultaneous burst.
- (iii) The nominal value of  $n_{\text{samp}}$  is 4 (i.e., 8 samples in total per BSM cycle) to ensure adequate sampling

of the waveform and to keep within the allowed data rate. With 2-Hz chop frequency and 4 samples per half-cycle, the samples are not statistically independent because of the integrating effect of the LPF – there is therefore little penalty in principle if they are not all used in the demodulation.

- (iv) The actual time of the first sample will be greater than the time of the command due to the synchronism with the bias waveform. We assume that there will be a pseudo-random delay of up to one bias period,  $T_b$ , (typically 8 ms for a bias frequency of 130 Hz).
- (v) The final sample in the set of  $n_{\text{samp}}$  need not be taken before the BSM is commanded to move again.

The chopped signal demodulation scheme (Section 6.6) must divide the signal waveform into two equal intervals phased in such a way as to maximise the demodulated signal level (i.e., it needs to be phase-synchronous).

Taking these considerations into account, the recommended sampling scheme for a particular case is described below. Note that this currently assumes no slow response – if there is a significant slow component, a problem may arise due to the sampling jitter because the “flat” part of the waveform is not flat. Implications of this for observing modes, data processing and photometric errors need to be assessed.

Bias frequency:	$f_b = 130 \text{ Hz}$
Bias period:	$T_b = 1/f_b = 7.68 \text{ ms}$
Number of samples per BSM position:	$n_{\text{samp}} = 4$
Sampling frequency:	$f_{\text{samp}} = f_b/7 = 18.60 \text{ Hz}$
Time between samples	$T_{\text{samp}} = 1/f_{\text{samp}} = 53.76 \text{ ms}$
Delay between BSM movement command and sample 1	$t_{\text{wait}} = 95 \text{ ms}$
Commanded times of the eight samples	95.0 148.8 202.5 256.3 345.0 398.8 452.5 506.3 ms
Latest possible times of the samples	102.7 156.4 211.0 264.0 352.7 406.4 460.2 514.0 ms

Note that the sampling frequency could be increased to  $\sim 20 \text{ Hz}$  without going beyond the available data rate.

The waveform and sample times are shown in Figure 19. The black and pink dots are separated by the bias period,  $T_b$ , and represent the extremes that may occur. Note that the possible delay in the range  $(0 - T_b)$  could be different for the positive and negative half cycles.

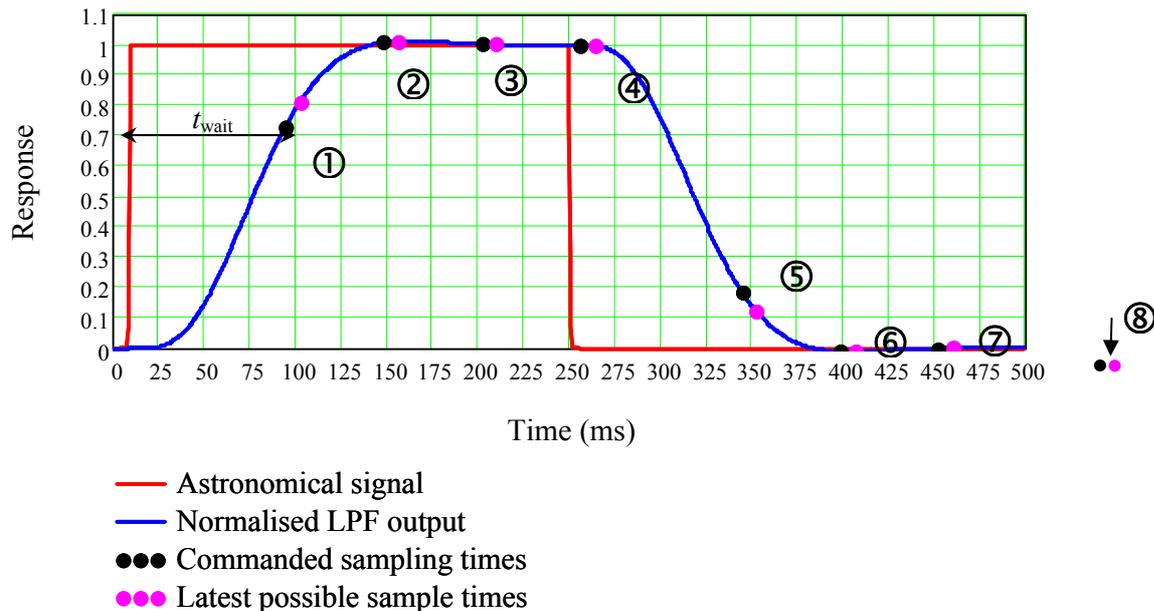


Figure 19: Eight signal samples over one BSM cycle for the example given in the text.

Because of the unpredictability of exactly when the samples are going to occur, the samples taken during the rise or fall period can vary significantly, making it inappropriate to use these for signal demodulation. Here we assume that the last three samples for each BSM position are to be used - i.e., samples sets (2, 3, 4) and (6, 7, 8) above.

In order to make the results insensitive to the potential variation in sampling times, it is necessary to optimise the delay between BSM motion and the initiation of the sampling sequence such that the three samples lie securely on the flat part of the waveform. Calculations have been done to determine the optimum value of  $t_{\text{wait}}$  and the corresponding variation in derived signal level arising from all possible combinations of delays in each half cycle. The demodulated signal varies by less than 0.1% over the whole range of possible sample distributions.

Note:

- (i) although the first sample in each half cycle is not used explicitly in the demodulation, it can be used for monitoring/diagnostic purposes if appropriate;
- (ii) the detailed sample timings will depend on the precise bias frequency and chop frequency adopted - the example above illustrates the method for devising the sampling and demodulation schemes;
- (iii) it would be desirable to have five samples per half-cycle if the telemetry rate permits.

In the pipeline, the demodulation must be carried out in terms of flux density in order to preserve linearity under all circumstances.

#### **4.4 Bolometer sampling in scan-map mode**

During scan-map observations, the **bolometers** will be sampled at 18.6 Hz. The time-shift between a sample and the corresponding position on the sky must be taken into account in the assignment of astrometric positions to the samples.

## 5. Scan-map pipeline

This section describes the various steps for the empirical scan-map pipeline. A number of these steps are the same in the jiggle-map pipeline described in Section 6.

Let the measured bolometer RMS voltage be

$$V_{d\text{-RMS}} = V_o + V_S, \quad (25)$$

where  $V_o$  is the operating point voltage under identical operating conditions but in the absence of any astronomical signal, and  $V_S$  is due to the astronomical signal ( $V_S$  is actually negative as the bolometer resistance decreases with increasing absorbed power). The behaviour of the operating point voltage as the photometric background on the bolometer is changed is illustrated in Figure 20, which shows the form of a bolometer load curve (current-voltage characteristic) under different conditions. The bolometer operating point ( $V_{d\text{-RMS}}, I_{d\text{-RMS}}$ ) is constrained to lie on the load line (by Ohm's law applied to the bias circuit). Further details and background can be found in Ref. [6].

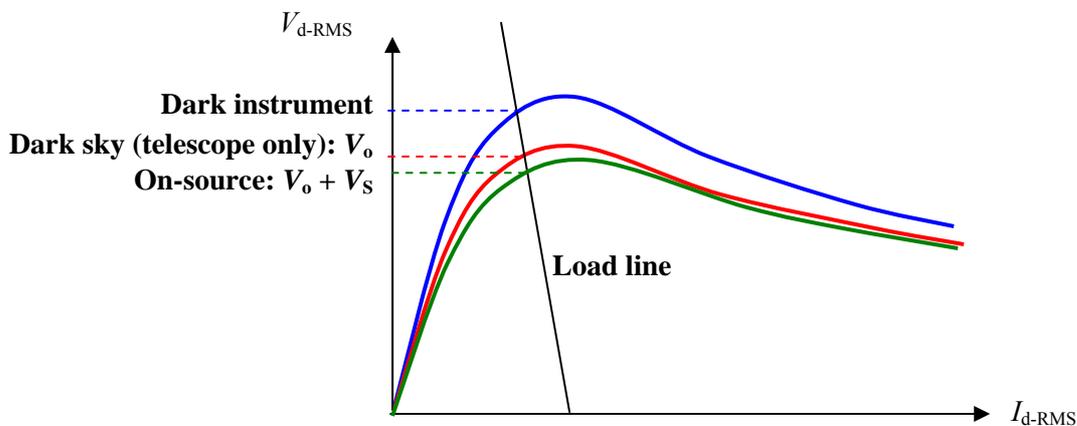


Figure 20: Dependence of operating point voltage on the operating conditions.  $V_o$  is the operating point voltage when viewing blank sky.  $V_S$  is the change from this voltage introduced by the source.

Note that:

- (i)  $V_o$  depends on the bolometer parameters, operating temperature, and bias setting, and on the background power from the telescope;
- (ii)  $V_S$  is linearly related to the source flux density for small signals, but there is a departure from linearity for large signals.

If  $V_o$  were known precisely, then it could be subtracted to allow a calculation of source flux density within the pipeline with no systematic offset. However, this is regarded as too ambitious, at least at this stage, because variations of  $V_o$  (with telescope background, instrument temperature and bolometer temperature) may be difficult to track. Therefore, a constant value will be assigned to  $V_o$  (for a given bolometer with a given bias setting). The  $V_o$  values for the bolometers will be determined by a blank sky observation under the nominal operating conditions, and should thus be close to the ideal values. (The offset subtraction and the method of accounting for non-linear bolometer response are further discussed in Section 5.5.)

### 5.1 Scan map pipeline flow diagram

Figure 21 shows the sequence of steps in the scan-map pipeline, and the individual modules are described in the subsections below.

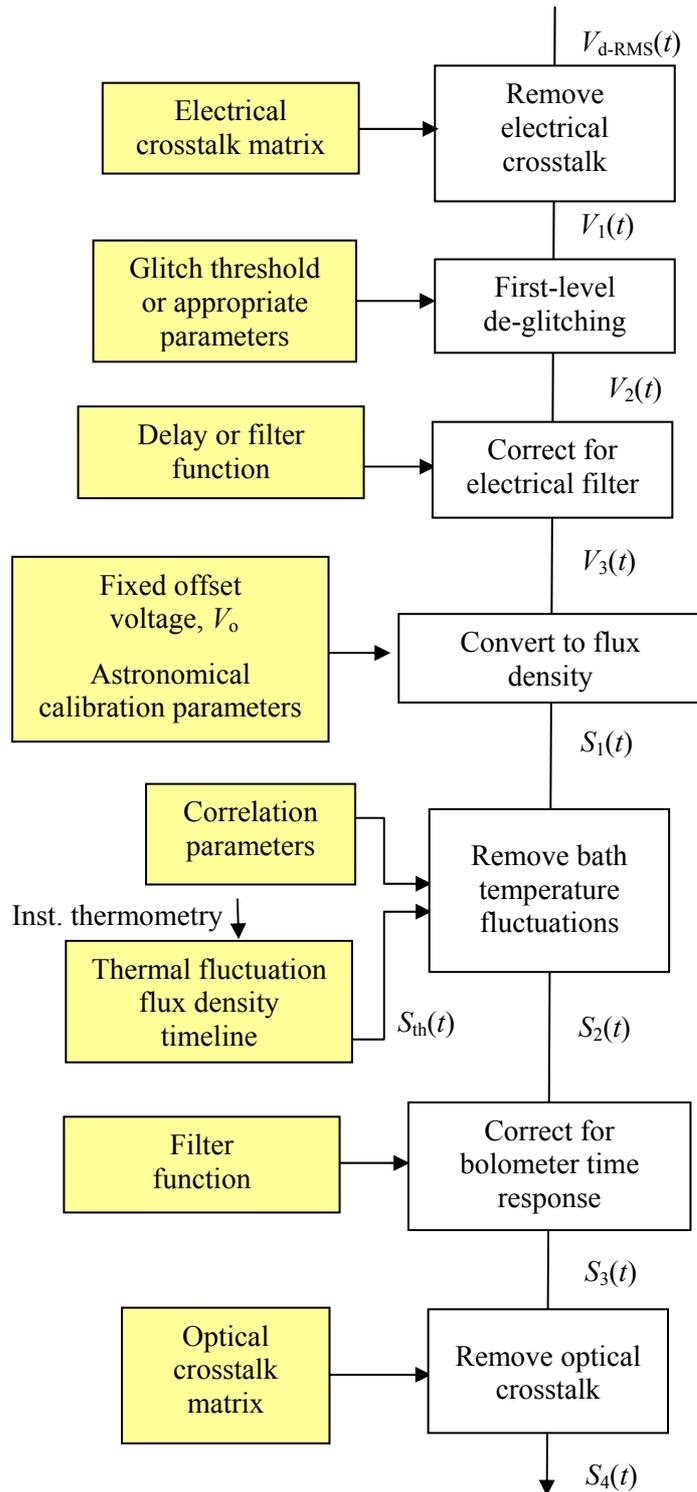


Figure 21: Pipeline block diagram for scan-map observations.

The first three modules (first-level deglitching, removal of electrical crosstalk and correction for the electrical filter) are applied to the voltage timelines as they can be regarded as electrical effects. After subtraction of the operating point voltage, the timelines are converted to units of astronomical flux density, a process which includes subtraction of the fixed offset voltage,  $V_o$ , and correction for the non-linear response to strong astronomical signals. Corrections are then made for other effects (bath temperature fluctuations, bolometer response, and optical crosstalk) which are linear when applied in terms of the power absorbed by the bolometer (which is proportional to flux density).

## 5.2 Remove electrical crosstalk

A signal voltage timeline might contain contributions that depend on the signals from other **bolometers** due to either electrical or optical crosstalk. Optical crosstalk occurs before the **bolometer** and is due to diffraction or aberrations in the optical system causing some of the power from an astronomical source to fall on inappropriate **bolometers**.

Electrical crosstalk can be removed if the coupling between the **bolometers** is known, and it is appropriate to do it at this stage. The removal of optical crosstalk can only be done after **bolometer** nonlinearity has been corrected and the constant telescope background has been subtracted (see Section 5.8).

Here we assume that electrical crosstalk is linear, so that the effects can be characterised by a crosstalk **matrix with** constant elements, and that there is no crosstalk between different arrays.

Electrical crosstalk can arise from

- (i) capacitive or inductive coupling between the **bolometer** readout channels;
- (ii) reduction in the **bolometer** bias voltage (which is common to a given array) due to loading of the bias supply by strong signals on multiple **bolometers**.

As explained below, these two effects can be corrected by successive matrix multiplication operations.

First we consider the crosstalk due to capacitive/inductive coupling. For a particular time-step, let us denote the vector of crosstalk-corrected signals by  $\mathbf{V}_{c1}$ , such that

$$\mathbf{V}_{c1} = \mathbf{C}_{e1} \mathbf{V}_{d-RMS}, \quad (26)$$

where  $\mathbf{C}_{e1}$  is the first crosstalk correction matrix and  $V_{c1-i}$  is the voltage for bolometer  $i$  corrected for capacitive/inductive coupling

As an illustration, if we had three **bolometers**, the matrix equation would be

$$\begin{bmatrix} V_{c1-1} \\ V_{c1-2} \\ V_{c1-3} \end{bmatrix} = \begin{bmatrix} 1 & e1_{21} & e1_{31} \\ e1_{12} & 1 & e1_{32} \\ e1_{13} & e1_{23} & 1 \end{bmatrix} \begin{bmatrix} V_{d-RMS-1} \\ V_{d-RMS-2} \\ V_{d-RMS-3} \end{bmatrix}. \quad (27)$$

Note that the unit diagonal elements embody an assumption that electrical crosstalk from one **bolometer** to another involves negligible diminution of the signal in the primary **bolometer**.

This crosstalk matrix can be implemented as a calibration file. Determination of the elements is a difficult problem. The **baseline plan** is to use the occasional ionising radiation hits that the bolometers will experience. Ideally, a single event in a bolometer produces a spike only in its own output; crosstalk results in this being accompanied by lower-level responses from other **bolometers**.

In the absence of **this kind of** crosstalk, or if the **correction** is to be left out, then the  $e1_{ij}$  coefficients are set to zero. If the crosstalk is low, then the off-diagonal elements should be small.

The second effect, **bolometer** de-biasing due to signals on the bolometers, is a known phenomenon and can be computed to generate the elements of the corresponding crosstalk matrix. Due to the nonzero series resistance between the bias voltage generator and the load resistors (Figure 1), when a bolometer resistance decreases by a large amount due to a radiation load, it draws extra current from the bias supply and the bias voltage amplitude seen by the other bolometers is reduced from  $V_b$  to  $V'_b$ . This produces a weak crosstalk voltage on each of the other bolometers which is approximately proportional to its dynamic impedance  $Z$ . Similarly, a moderate signal which is common to many of the bolometers drags down the bias and produces crosstalk in all of the other channels, including the resistors and **thermistors**.

This crosstalk through the bias could be handled exactly in the model-based pipeline. For the empirical pipeline, we use a small-signal approximation to generate a linear transformation of the signals to estimate what their values would be in the case that  $R_b = 0$ , i.e.,  $V_b' = V_b$ .

It can be shown that the loaded-down bias voltage is given by:

$$V_b' = \frac{\frac{V_b}{R_b} + \sum_{\text{Array}} \frac{V_{c1-i}}{R_{Li}}}{\frac{1}{R_b} + \sum_{\text{Array}} \frac{1}{R_{Li}}}, \quad (28)$$

where for bolometer  $i$ ,  $R_{Li}$  is the load resistance of the bolometer;  
 $Z_i$  is the dynamic impedance of the bolometer ( $dV_i/dI_i$ ); and  
 $V_{d-RMS-i}$  is the measured bolometer voltage.

The response of bolometer  $i$  to this change in bias is estimated to be:

$$\Delta V_i = \Delta V_b \left[ \frac{Z_i}{R_{Li} + Z_i} \right]. \quad (29)$$

The hypothetical change in bias amplitude from  $V_b'$  to  $V_b$  therefore results in an estimated corrected bolometer signal:

$$V_{c2-i} = V_{c1-i} + \left[ \frac{Z_i}{R_{Li} + Z_i} \right] \left[ \frac{V_b \sum_{\text{Array}} \frac{1}{R_{Li}} - \sum_{\text{Array}} \frac{V_{c1-i}}{R_{Li}}}{\frac{1}{R_b} + \sum_{\text{Array}} \frac{1}{R_{Li}}} \right]. \quad (30)$$

The  $Z_i$  values can be estimated from bolometer modelling before flight, and in flight from dedicated calibration measurements involving a small increment to the bias voltage.

This linear transformation removes the crosstalk associated with the bias circuit and can be implemented by a second crosstalk correction matrix,  $\mathbf{C}_{e2}$ , to generate the final crosstalk-corrected bolometer voltages:

$$\mathbf{V}_1 = \mathbf{C}_{e2} \mathbf{V}_{c1}. \quad (31)$$

For example, if we had three bolometers, this matrix equation would be:

$$\begin{bmatrix} V_{1-1} \\ V_{1-2} \\ V_{1-3} \end{bmatrix} = \begin{bmatrix} e2_{11} & e2_{21} & e2_{31} \\ e2_{12} & e2_{22} & e2_{32} \\ e2_{13} & e2_{23} & e2_{33} \end{bmatrix} \begin{bmatrix} V_{c1-1} \\ V_{c1-2} \\ V_{c1-3} \end{bmatrix}. \quad (32)$$

The final crosstalk-corrected timeline for bolometer  $i$  is denoted  $V_{1-i}(t)$  and is the input timeline for the next module.

### 5.3 First-level deglitching

Before further processing of the crosstalk-corrected bolometer voltage timeline,  $V_{1-i}(t)$ , glitches due to cosmic ray hits or other impulse-like events in the bolometers will be removed. Two options are considered:

Option 1: A simple algorithm is implemented in which the signature of the system response to an impulse (above some specified threshold which will depend on the noise level) is registered. The corresponding data samples are removed from the timeline and/or flagged as corresponding to a glitch.

Option 2: A more sophisticated approach is described in Ref. [5], based on a local regularity analysis combined with a wavelet analysis. This scheme needs to be evaluated for use in the photometer pipeline. In principle, the same method should be applicable in both pipelines.

For the moment, we assume that Option 2 is also to be implemented for the photometer scan map mode. **In either case, the samples removed from the timeline must be replaced with suitably interpolated values.**

This module should be applied to the complete **bolometer** timeline (from the start of telescope acceleration to the end of the deceleration) since the acceleration and deceleration periods may be used later for scientific purposes, and to make sure that data at the start and end of the nominal scan region are correctly de-glitched.

The output of this module is the de-glitched voltage timeline,  $V_{2-i}(t)$  for **bolometer**  $i$ .

#### 5.4 Correction for electrical filter response

As shown in Section 4.2, the electronics chain imposes a delay on the data with respect to the telescope position along the scan; this effect must be taken into account to ensure that the astrometric pointing timeline is properly matched to the **bolometer** data timeline. Correction for the bolometer response is done later in the pipeline (see Section 5.7). To correct for the effect of the electrical filter alone, there are two options:

Option 1:

- (i) Fourier transforming each **bolometer** timeline  $V_{2-i}(t)$ ;
- (ii) multiplying the FT by an appropriate complex correction function  $CF_{1-i}(\omega)$ , based on the **normalised** LPF transfer function (**equation (13) with the DC gain term set to unity**);
- (iii) transforming back to the time domain to obtain the corrected signal voltage,  $V_{3-i}(t)$ .

**Note that  $CF_{1-i}(\omega)$  must be normalised to unity at zero frequency because the DC gain term of the LPF is already taken into account in the total gain term in the conversion of the telemetry numbers to voltage by equation (17).**

**This procedure corrects for both the amplitude and phase (time delay) effects of the LPF on the bolometer timeline.** The relevant calibration information is the correction function, which will be derived from calibration file parameters stored for each **bolometer** (LPF transfer function parameters) – nominally the same for all **bolometers**.

This module should be applied to the complete **bolometer** timeline (from the start of telescope acceleration to the end of the deceleration) since the acceleration and deceleration periods may be used later for scientific purposes, and to make sure that any ringing effects at the start and end of the scan caused by the Fourier transformations are well clear of the nominal map area.

Option 2:

An alternative approach, which is simpler and almost as accurate is to impose a fixed delay to the timeline based on the response of the system to a Gaussian input. As shown in Section 4.2, implementing a delay of 74 ms results in less than 0.5% distortion for the nominal scan speed of  $30'' \text{ s}^{-1}$ , and less than 2% for  $60'' \text{ s}^{-1}$ . There are two options for the format of the output timelines:

- (i) keep the **bolometer** samples and change the timestamps by subtracting the fixed delay from each (not preferred as it would decouple the timestamps in the telemetry from those in the commands);
- (ii) keep the timestamps and interpolate to derive corrected **bolometer** samples (preferred).

The nominal sampling rate is 18.6 Hz. The sampling interval is thus 53.8 ms, so the delay is not an integer number of samples. The worst-case (PSW) number of samples per FWHM-crossing time is 11.2 for 30"/s and 5.6 for 60"/s. So in all cases, the sampling of the response to a point source is better than Nyquist. It is therefore acceptable to implement the delay by interpolation between samples if desired.

As the baseline, Option 1 will be implemented. The output timelines should contain the original timestamps with modified **bolometer** signal values attached.

The filter corrected timeline for **bolometer**  $i$  is denoted  $V_{3-i}(t)$ .

The bolometer resistance timeline must be similarly modified to ensure that the resistance and voltage timelines are correctly matched. The **bolometer** resistance is related to the measured **bolometer** voltage, the bias voltage, and the load resistance as follows:

$$R_{d-i}(t) = \frac{V_{3-i}(t)R_L}{V_{b-RMS} - V_{3-i}(t)}. \quad (33)$$

Note that this module must therefore have access to  $V_{b-RMS}$  and  $R_L$  values.

## 5.5 Conversion to flux density

This section describes the method to be used to derive the in-beam flux density, including flat fielding and strong source corrections.

The in-beam astronomical flux density at a given frequency,  $\nu$ , is defined as follows:

$$S(\nu) = \oint_{4\pi} B(\theta, \phi) I_\nu(\theta, \phi) d\Omega = \int_0^{2\pi} d\phi \int_0^\pi B(\theta, \phi) I_\nu(\theta, \phi) \sin\theta d\theta, \quad (34)$$

where  $\theta$  ( $= 0 - \pi$ ) is a radial angular offset from the beam centre,  $\phi$  ( $= 0 - 2\pi$ ) is an azimuthal angular offset,  $B(\theta, \phi)$  is the normalised beam profile, and  $I_\nu(\theta, \phi)$  is the sky intensity (surface brightness) profile, and  $d\Omega$  is a solid angle element in the direction defined by  $(\theta, \phi)$ . In practice the integral can be computed over a limited range of  $Y$  and  $Z$  angular offsets:

$$S(\nu) = \iint_{y, z} B(y, z) I_\nu(y, z) dydz. \quad (35)$$

Note that we will assume here that the beam profile  $B(y, z)$  can be regarded as uniform across the spectral passband.

The absorbed **bolometer** power due to an astronomical source depends on the flux density at the aperture. The quantity that is directly proportional to absorbed **bolometer** power is the integral over the band of the flux density weighted by the instrument relative spectral response function (RSRF),  $R(\nu)$ :

$$\bar{S} = \frac{\int_{Passband} S(\nu) R(\nu) d\nu}{\int_{Passband} R(\nu) d\nu} \quad (36)$$

where  $S(\nu)$  represents the source spectrum and  $R(\nu)$  is the instrument Relative Spectral Response Function (RSRF). Derivation of a monochromatic flux density requires definition of a standard frequency for the band and some assumption about the shape of the source spectrum.

For an NTD bolometer with a given applied bias voltage, the small-signal responsivity varies with the voltage across the bolometer with an approximately linear relationship over a wide range of background loading and bath temperature conditions [6]. This translates to a corresponding relationship for the differential sensitivity of the system to  $\bar{S}$ . Writing  $V_{\text{d-RMS}}$  as  $V$ , we have

$$\frac{dV}{dQ} \propto V \Rightarrow \frac{dV}{d\bar{S}} \propto V . \quad (37)$$

To allow for the fact that the responsivity–operating point voltage relationship will not be exactly linear, we let

$$\frac{d\bar{S}}{dV} = f(V), \quad (38)$$

Note that:

- (i)  $f(V)$  is specific to a particular **bolometer** and bias setting;
- (ii)  $f(V)$  is negative (nominally  $V_3 < V_0$  since absorbed power causes a decrease in bolometer voltage); however, in the rest of this document we take it to be positive for convenience, assuming that a correction factor of -1 is applied..

In order to perform integration of  $f(V)$ , we can fit an approximating function to it. Various fitting functions have been investigated [Ref. note to be provided by Darren] and it is found that the most suitable function is of the form:

$$f(V) = K_1 + \frac{K_2}{V - K_3}, \quad (39)$$

where  $K_1$ ,  $K_2$  and  $K_3$  are constants.  $K_1$  has units of  $\text{Jy V}^{-1}$ ,  $K_2$  has units of  $\text{Jy}$ , and  $K_3$  has units of  $\text{V}$ .

A typical plot of  $f(V)$  vs.  $V$  is shown in Figure 22, and corresponds to a nominal PMW **bolometer**. The nominal operating point (blank sky) in this case would be around 3 mV, and the range covered by the plot covers a sky brightness range up to more than 10 times the telescope brightness. The blue points are derived from a bolometer model, and the red line corresponds to the best fit  $K$ -parameters using equation (39).

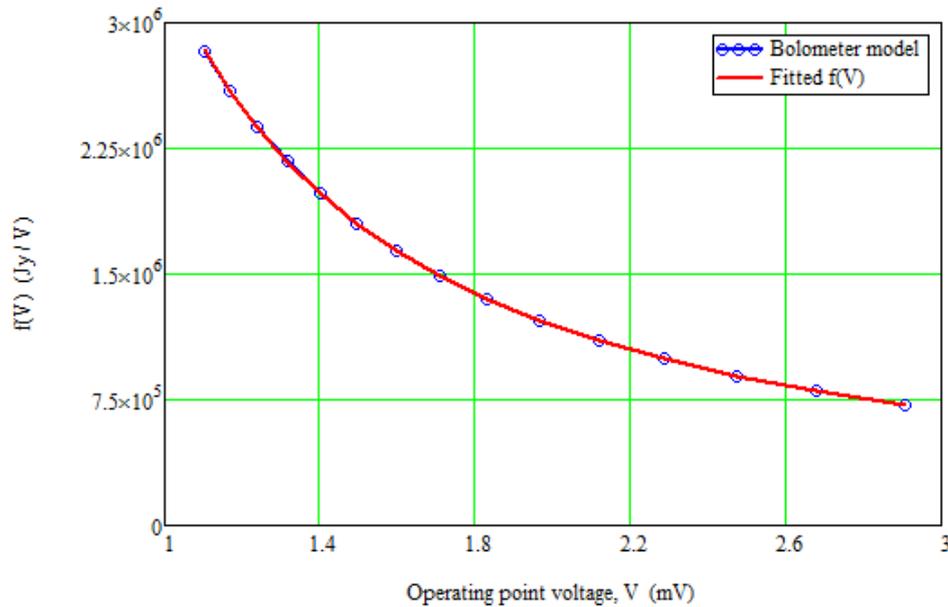


Figure 22: Typical plot of  $f(V)$  vs  $V$  (for a nominal PMW **bolometer**). The blue points correspond to the bolometer model and the red line is the fitted function using equation (39).

The derivation of the  $K$ -values and the astronomical calibration scheme are described in more detail in Section 7.

A flux density corresponding to a measured RMS **bolometer** voltage,  $V_m$ , can be derived by integrating the above expression between some fixed **bolometer** voltage,  $V_o$ , and  $V_m$ :

$$\bar{S} = \int_{V_o}^{V_m} f(V) dV . \quad (40)$$

Ideally,  $V_o$  should be the bolometer voltage in the absence of any astronomical signal (i.e., what would be measured when observing blank sky in otherwise identical conditions). The resulting flux density would correspond to that from the sky calibrated with respect to the dark sky level.  $V_o$  will therefore be derived from standard calibration observations of a “dark” area of sky in scan-map mode, to produce a calibration file containing the offset voltages,  $V_{o,i}$ , for the **bolometers** under the nominal conditions: bias voltage and frequency; **bolometer** and instrument FPU (Level-1) temperature, and telescope temperature. Although ideally the conditions would be the same for the calibration and science observations, small differences are likely in practice. We therefore expect  $V_o$  will differ from the ideal value (by an amount much larger than most astronomical signals). This means that the initial flux density values produced in this step will have additive offsets (different for each **bolometer**) that must be removed later to derive the flux density from the sky. The most effective approach is to do this as part of the map-making process (see Section 5.9). With cross-linked maps, which are recommended for most scan-map observations, this is done naturally as part of the map-making routine.

The **bolometer** voltage is converted to flux density by integrating  $f(V)$  between the limits  $V_o$  and  $V_3$ :

$$\bar{S} = \int_{V_o}^{V_3} \left( K_1 + \frac{K_2}{V - K_3} \right) dV , \quad (41)$$

so

$$\bar{S} = K_1(V_3 - V_o) + K_2 \ln \left( \frac{V_3 - K_3}{V_o - K_3} \right) . \quad (42)$$

SPIRE flux densities will be quoted as monochromatic values at a standard frequency for each band, under the assumption of a particular standard source spectral index. The calibration scheme is described in Section 7.3, where it is shown that the RSRF-weighted flux density,  $\bar{S}$ , is related to the monochromatic flux density by a dimensionless constant,  $K_4$ , (derived from the RSRF, the standard frequency, and the assumed source spectral index). The final step in this module is therefore to multiply  $\bar{S}$  by  $K_4$  to derive the first estimate of the source flux density:

$$S_1 = K_4 \bar{S}. \quad (43)$$

In the pipeline implementation,  $K_4$  will be incorporated as a multiplicative factor modifying  $K_1$  and  $K_2$ .

The output of this module is a set of timelines corresponding to the first estimates of flux densities:  $S_{1-i}(t)$  for **bolometer**  $i$ .

### 5.6 Remove correlated noise due to bath temperature fluctuations

To first order, bath temperature fluctuations will influence all **bolometers** in an array coherently – the temperature and corresponding output voltages will go up and down in synchronism. The  $^3\text{He}$  bath temperature,  $T_o$ , may fluctuate due to temperature drifts within the instrument.

For the level of fluctuations expected in SPIRE, the most important effect of bath temperature variations will be the direct response of the **bolometer** output voltage. Because bath temperature fluctuations replicate the effect of absorbed power fluctuations on the bolometer output, it is best to correct for them after the conversion to flux density (which is proportional to power). There will be a small second-order effect on the **bolometer** small-signal responsivity. Fluctuations in  $T_o$  are expected to be much slower than the nominal chopping frequency of 2 Hz, so that the correction will only be needed for scan-map observations. There are two options for removing the correlated thermal noise contributions to the bolometer timelines:

1. use of the correlations between the **bolometer** outputs themselves;
2. use of the correlations between the **bolometers** and the array **thermistors** or **dark bolometers**.

For Option 1, the procedure is as follows:

- take the median signal timeline of all the **bolometers** in an array (or perhaps a set of them around the periphery of a “source” – but that has to be done at the level of the map rather than the timeline);
- adjust the median timeline so that its mean is zero;
- subtract this from each individual **bolometer** timeline

This method will not introduce much additional noise as the timeline to be subtracted is averaged over many **bolometers**. However, there are two problems with this method: firstly, for scanning observations, large-scale sky structure can mimic bath temperature fluctuations (all the **bolometers** going up and down together) and so can be removed by this process; secondly, the presence of strong emission in a part of the map will bias the median timeline, resulting in potential removal of some real signal.

Option 2 involves generating a voltage timeline  $V_{\text{th-}i}(t)$  from the array **thermistor** timelines. A scaled version of this is then subtracted from that **bolometer**'s signal timeline. To avoid introducing additional noise, the thermometry timeline will need to be significantly less noisy than the bolometer signals. It will therefore need to be averaged over a period of time such that it becomes a negligible fraction (say 10%) of the **bolometer** noise. This will require a suitable averaging period. Thermal fluctuations on timescales shorter than this will not be tracked.

In order to have a scheme that involves minimal loss or distortion of the astronomical signal, Option 2 is to be adopted as the baseline. The detailed implementation has been defined by JPL/IPAC following evaluation and refinement of the method using ILT data. A period on the order of a second or a few seconds is suitable, and is adequate to correct the timelines at the low frequencies where the temperature fluctuations dominate the **bolometer** noise. It should be that although the **thermistor** averaging procedure removes the high frequency components of the **thermistor** noise, the low frequency noise of the **thermistor** actually raises the noise level on the corrected bolometer timeline compared to the case of perfect temperature stability and

no correction. The choice of averaging period will need to be based on careful assessment of the in-flight performance, particularly the  $1/f$  characteristics of the **thermistor** noise spectrum.

The correction will be implemented in the following way:

Let  $\bar{V}_{T_1}$  and  $\bar{V}_{T_2}$  be the smoothed voltage timelines of **thermistors**  $T_1$  and  $T_2$  for a given array. These are converted to flux density timeline for **bolometer**  $i$  as follows:

$$S_{T_1-i}(t) = A_{1-i}(\bar{V}_{T_1} - V_{01}) + 0.5B_{1-i}(\bar{V}_{T_1} - V_{01})^2, \quad (44)$$

$$S_{T_2-i}(t) = A_{2-i}(\bar{V}_{T_2} - V_{02}) + 0.5B_{2-i}(\bar{V}_{T_2} - V_{02})^2, \quad (45)$$

where  $V_{01}$  and  $V_{02}$  are reference signals of  $T_1$  and  $T_2$ , measured during calibration observations, and  $A_{1-i}$ ,  $B_{1-i}$  and  $A_{2-i}$ ,  $B_{2-i}$  are correlation coefficients for **bolometer**  $i$ .

These timelines can be used individually or averaged to generate the final correction timeline:

$$S_{T-i}(t) = S_{T_1-i}(t) \quad \text{or} \quad S_{T-i}(t) = S_{T_2-i}(t) \quad \text{or} \quad S_{T-i}(t) = \frac{1}{2}[S_{T_1-i}(t) + S_{T_2-i}(t)]. \quad (46)$$

The best choice will depend on the detailed performance of the **thermistors** on the different arrays.

The corrected **bolometer** timeline for **bolometer**  $i$  is given by:

$$S_{2-i}(t) = S_{1-i}(t) - S_{T-i}(t) \quad (47)$$

At the high bias voltage setting, the **thermistors** will be saturated, and the temperature drift will be traced by dark **bolometers**. Therefore, for the high bias voltage, the dark **bolometer** voltages  $V_{DK}$  will be used instead of the thermistor voltages  $V_T$ .

The output of this module is a set of timelines of astronomical flux densities corrected for low-frequency thermal drifts:  $S_{2-i}(t)$  for **bolometer**  $i$ .

### 5.7 Correct for bolometer time response

The bolometer transfer function is represented as a two-component system as described in Section 4. The baseline plan to correct for the slow **bolometer** time constant is to use the following procedure:

- (i) Fourier transforming each signal timeline  $S_{S_{2-i}}(t)$ ;
- (ii) multiplying the FT by an appropriate correction function  $CF_{2-i}(\omega)$ ;
- (iii) transforming back to the time domain to obtain the corrected estimate of the signal,  $S_{S_{3-i}}(t)$

The relevant calibration information is the correction function, derived from the bolometer transfer function  $H_{Bol}(\omega_s)$  (see Section 3.8.24) which will be derived from calibration file parameters stored for each **bolometer**:

- (i) nominal **bolometer** time constant,  $\tau_{1-i}$
- (ii) slow **bolometer** time constant,  $\tau_{2-i}$
- (iii) time constant amplitude factors,  $a_i$ .

Note that  $\tau_{2-i}$  and  $a_i$  are not currently known (although some upper limits may be derived from ILT data) and will be estimated from PV-Phase measurements.

The output of this module is a new set of timelines corresponding to the in-beam astronomical flux densities now corrected for the bolometer response:  $S_{3,i}(t)$  for **bolometer**  $i$ . The output timelines should contain the original timestamps with modified **bolometer** signal values attached.

Implementation of this module is TBC depending on

- (i) confirmation that there are no technical impediments and that the noise level is not degraded, and
- (ii) confirmation (in flight) that **the** effect of the slow bolometer response is significant enough to require correction.

The output of this module is a set of timelines of astronomical flux densities corrected for the bolometer time response:  $S_{3,i}(t)$  for **bolometer**  $i$ .

### 5.8 Remove optical crosstalk

Optical crosstalk is here defined as power from the astronomical sky that should be incident on one **bolometer** actually falling on another. It is important to note that in the case of SPIRE, neighbouring **bolometers** are separated by an angle of  $2\lambda/D$  on the sky, and even if a source is on-axis for a given **bolometer**, some fraction of the source power will be incident on the neighbouring **bolometers** due to telescope diffraction. Non-neighbouring **bolometers** are sufficiently far apart that they should not pick up any power from an on-axis source.

Optical crosstalk can be characterised by a crosstalk matrix,  $\mathbf{C}_{\text{opt}}$ , analogous to the electrical crosstalk matrix described in Section 5.2. Let  $\mathbf{S}_3$  be the input vector of flux densities for a given time step.

The vector of optical crosstalk-corrected flux densities is then given by

$$\mathbf{S}_4 = \mathbf{C}_{\text{opt}} \mathbf{S}_3 \quad (48)$$

As an illustration, if we had three **bolometers**, the matrix equation would be

$$\begin{bmatrix} S_{4-1} \\ S_{4-2} \\ S_{4-3} \end{bmatrix} = \begin{bmatrix} o_{11} & o_{21} & o_{31} \\ o_{12} & o_{22} & o_{32} \\ o_{13} & o_{23} & o_{33} \end{bmatrix} \begin{bmatrix} S_{3-1} \\ S_{3-2} \\ S_{3-3} \end{bmatrix} \quad (49)$$

Unlike the case of electrical crosstalk, the diagonal elements are not equal to unity since optical crosstalk involves loss of power from the primary **bolometer**.

In the absence of optical crosstalk, or if the crosstalk correction is to be left out, then the non-diagonal  $o_{ij}$  coefficients are set to zero and the diagonal coefficients are set to unity.

The optical crosstalk matrix can be implemented as a calibration file. The values of  $o_{ij}$  must be determined from calibration observations involving scanning a strong point source across each of the **bolometers** in the array. Optical crosstalk correction may be complicated due to ghost images from reflections being dependent on source position (and so variable). Until such effects have been evaluated in flight, it may be appropriate to use the identity matrix except for cases of obvious constant ghost images.

The output of this module is a set of flux density timelines:  $S_{4,i}(t)$  for **bolometer**  $i$ , suitable for input to the map-making module.

### 5.9 Map-making

Scan-map observations will be processed using an implementation of the maximum likelihood map-making algorithm MADmap [7]. This type of algorithm makes use of the redundant information from cross-linked observations to establish a noise covariance matrix which is then used to down-weight the contribution from  $1/f$  noise to the map, and is widely used by cosmic microwave background (CMB) experimenters. Greater

levels of cross-linking enable a maximum likelihood map-maker to operate more effectively. As a result, this method is dependent on the observing strategy used. If cross-linked observations are not performed, then the output from this algorithm will be a naïve map (i.e. a map in which each **bolometer** value is equal to the average value of all of the measurements falling within the pixel area) as this is the optimal map reconstruction for data obtained via a non-cross-linked scanning strategy.

It has been suggested that the timelines of in-beam flux density should be converted to units of MJy Sr<sup>-1</sup> prior to the mapmaking process. This requires dividing by the beam solid angle, defined by

$$\Omega_{\text{Beam}} = \oint_{4\pi} B(\theta, \phi) \, d\Omega = \int_0^{2\pi} d\phi \int_0^{\pi} B(\theta, \phi) \sin\theta \, d\theta \quad (50)$$

where the symbols are as defined in Section 5.5. The beam solid angles can be found from the measured in-flight beam profiles. Prior to launch, they can be estimated from the beam profile models which are already available. In practice the integral can be computed over a limited range of Y and Z angular offsets:

$$\Omega_{\text{Beam}} = \iint_{y, z} B(y, z) \, dydz \quad (51)$$

If this is implemented then, the Mapmaking module will need to incorporate the  $\Omega_{\text{Beam}}$  values (nominally one for each array).

Instrument and housekeeping data that should be available in mapmaking to assist in possible further removal of correlations:

- Telescope temperature (unlikely to be influential as timescale for variation is expected to be very long - days or weeks).
- Level-1 temperature (most likely to be influential, especially at long wavelengths, as it produces a significant background on the **bolometers**)
- <sup>3</sup>He temperature (already corrected in the pipeline, but should be made available in case further correlations can be discerned and corrected)
- Level-0 temperature (unlikely to be influential since the L0 temperature is too low to produce a significant background on the **bolometer** – but may be correlated with **bolometer** fluctuations via conductive thermal behaviour).

In future versions of the pipeline, based on extensive in-flight experience, it is conceivable that such correlations could be removed in the pipeline before the map-making stage.

## 6. Point source and jiggle-map pipeline

### 6.1 Signals measured during chopping and nodding

There are some key differences between the pipelines for chopped photometric observation and scan map observations:

- (i) for chopped observations, there is no need to correct for low-frequency noise associated with bath temperature fluctuations: it is assumed that such fluctuations are at frequencies lower than the chop frequency and so are chopped out;
- (ii) in the case of chopped and noded observations, the observation is inherently differential, and the calculated source flux density is measured with respect to the sky background in the vicinity of the source.

Due to small asymmetries in the optical system, the ambient background power in the two chop positions will be slightly different. The purpose of nodding is to subtract out this difference.

The principles of chopping and nodding are illustrated in Figure 23, in which the three positions viewed by one bolometer during the sequence are illustrated. Chopping and nodding are along the spacecraft Y axis. The two chop positions are denoted  $Y_P$  and  $Y_N$ , with  $Y_P$  (positive) being the one with the more positive Y position and  $Y_N$  (negative) the one with the more negative Y position. The two nod positions are designated A and B, with position B being the more positive in Y. In the case illustrated, we assume that there is a source of flux density  $S_S$  in the position that is common to both nod positions, and that the sky background varies with position, having values  $S_{b1}$ ,  $S_{b2}$ , and  $S_{b3}$  in the three positions observed by the bolometer.

Let  $S_{oP}$  and  $S_{oN}$  be the flux densities that would be derived from the bolometer outputs in the right and left beams for completely blank sky (these are entirely generated entirely locally, and have nothing to do with the sky brightness.  $S_{oP}$  and  $S_{oN}$  are unequal because the bolometer does not view the local (instrument and telescope) background identically in the two BSM positions).

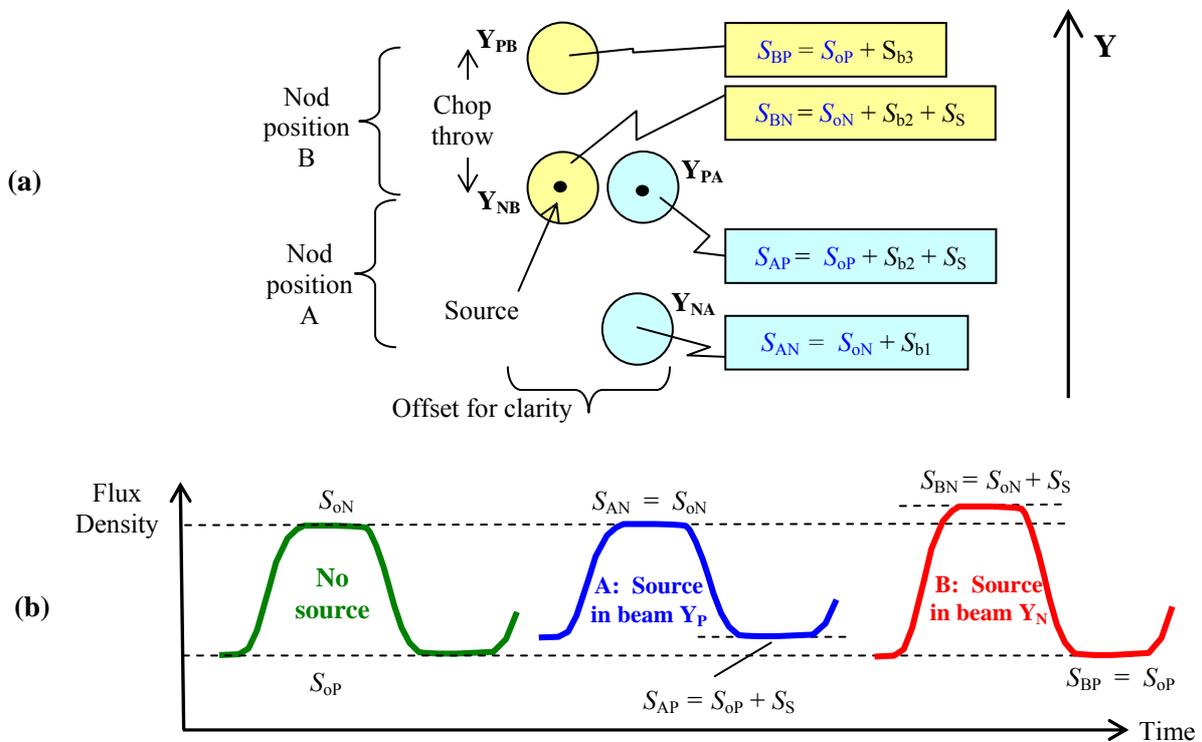


Figure 23: (a) Flux density levels measured during chopping and nodding. (b) Example timelines for nod positions A and B (with the source in the right beam for position A), where for simplicity the sky background is taken to be zero.

Referring to Figure 23(a), the de-modulated chopped signal (beam  $Y_P$  – beam  $Y_N$ ) for nod position A is  $S_A = (S_{oP} + S_{b2} + S_S) - (S_{oN} + S_{b1})$ , whilst that for position B is  $S_B = (S_{oP} + S_{b3}) - (S_{oN} + S_{b2} + S_S)$ . The difference (de-modulated nod signal) is thus  $S_A - S_B = 2S_S + (S_{b2} - S_{b1}) - (S_{b3} - S_{b2})$ . The flux density offset due to the asymmetric ambient background has thus been subtracted. If the sky background is uniform or varying linearly, it is removed. If there is a higher order variation in sky brightness, then it will not be completely subtracted.

The above analysis is valid in the case of an observation of a particular sky position by a single **bolometer**. In the case of point source observations, for a given array three **bolometers** see the source at some time during the observation, as shown in Figure 24. The primary **bolometer** sees it in both nod cycles, as illustrated in Figure 23; however, the other two only see it in one of the nod positions.

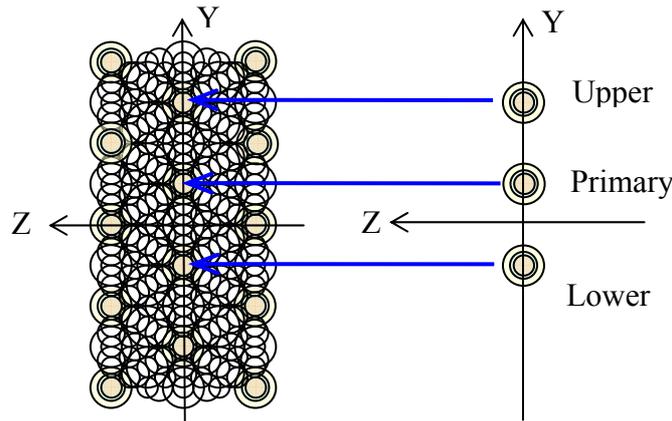


Figure 24: Nominal **bolometer** sets used for point source photometry.

In the course of the observation, five different sky positions are viewed by the three **bolometers** (per array). The corresponding signals are indicated in Figure 25, which also shows the positions viewed by the lower **bolometer** during the chopping and nodding cycles. Let the sky background flux density in the five positions be  $S_{b0} \dots S_{b4}$ , and let the source position coincide with  $S_{b2}$ .

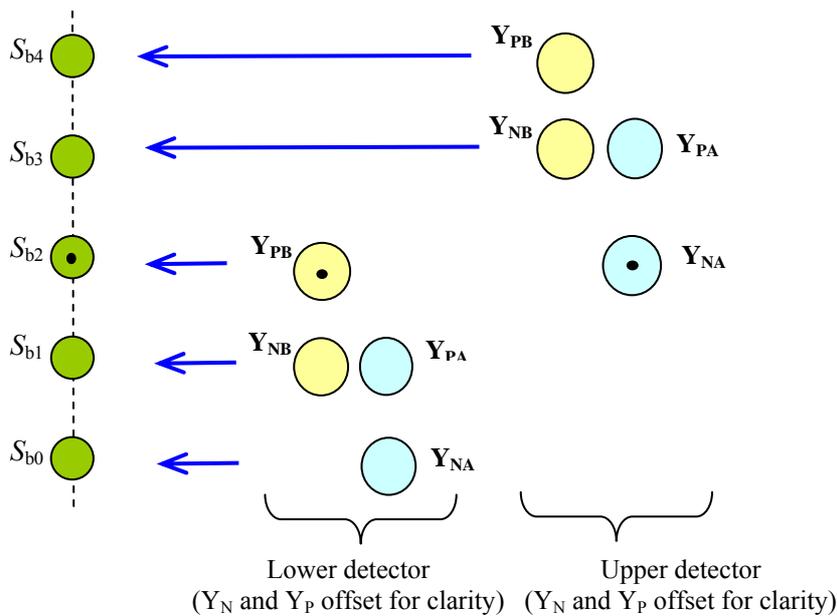


Figure 25: Five sky positions viewed by the three **bolometers** involved in point source photometry, and positions observed by the lower and upper **bolometer** set during chopping and nodding.

Then, for the lower **bolometer** we have:

$$\begin{aligned}
\text{Demodulated } (Y_P - Y_N) \text{ signal for nod position A:} & S_A &= (S_{oP} + S_{b1}) - (S_{oN} + S_{b0}) \\
\text{Demodulated } (Y_P - Y_N) \text{ signal for nod position B:} & S_B &= (S_{oP} + S_{b2} + S_S) - (S_{oN} + S_{b1}) \\
\text{Difference (de-nodded signal):} & S_A - S_B &= 2S_{b1} - (S_{b0} + S_{b2}) - S_S
\end{aligned}$$

Similarly, for the upper **bolometer** we have:

$$\begin{aligned}
\text{Demodulated signal for nod position A:} & S_A &= (S_{oP} + S_{b3}) - (S_{oN} + S_{b2} + S_S) \\
\text{Demodulated signal for nod position B:} & S_B &= (S_{oP} + S_{b4}) - (S_{oN} + S_{b3}) \\
\text{Difference (de-nodded signal):} & S_A - S_B &= 2S_{b3} - (S_{b4} + S_{b2}) - S_S
\end{aligned}$$

Note that  $S_{oP}$  and  $S_{oN}$  can be different for different **bolometers** (but this does not matter as these offsets are removed per **bolometer** in the de-nodding)

If the sky background is uniform or linear, then  $2S_{b1} = (S_{b0} + S_{b2})$  and  $2S_{b3} = (S_{b4} + S_{b2})$ , so we have

$$S_A = -S_S \quad \text{and} \quad S_B = -S_S. \quad (52)$$

We therefore get two additional estimates of the source signal, of half the magnitude as for the primary **bolometer** (but with the same noise level).

So the point source observation produces three separate estimates of the source flux density:  $2S$  for the primary **bolometer** and  $S$  for each of the upper and lower **bolometers**. Let the **signal-to-noise ratio** for the central **bolometer** be  $SNR$ , and assume that the three **bolometers** have equal sensitivity. In that case the S/N for the upper and lower **bolometers** is  $SNR$ . If the three measurements are combined, the overall S/N is thus

$$SNR_{tot} = \left[ SNR^2 + 2 \left( \frac{SNR}{2} \right)^2 \right]^{1/2} = \left[ \frac{3}{2} \right]^{1/2} SNR = (1.22) SNR \quad (53)$$

The pipeline should calculate and quote the three estimates of the source flux density separately, and provide an option to combine them if the user so desires. Differences in the three measured values may be used to identify non-linear sky gradients.

## 6.2 Point source and jiggle map pipeline flow diagram

The SPIRE pipeline must operate over a wide range of source brightness, and the direct proportionality of voltage to flux density cannot be assumed. It is therefore necessary to carry out the demodulation process *after* conversion to flux density (see Section 6.5 below).

The number of BSM (jiggle) positions in a map is  $N_{jig} = 7$  or  $64$ , depending on the AOT. Each **bolometer** generates  $N_{jig}$  data points for the map in the form of flux density values ascribed to each jiggle position. Figure 26 shows, for one jiggle position of one **bolometer**, the sequence of steps in the point source and jiggle-map pipeline, and the individual modules are described in the subsections below. It produces the data for one map point (flux density and statistical error) for each nod cycle (not that the number of nod cycles is nominally one).

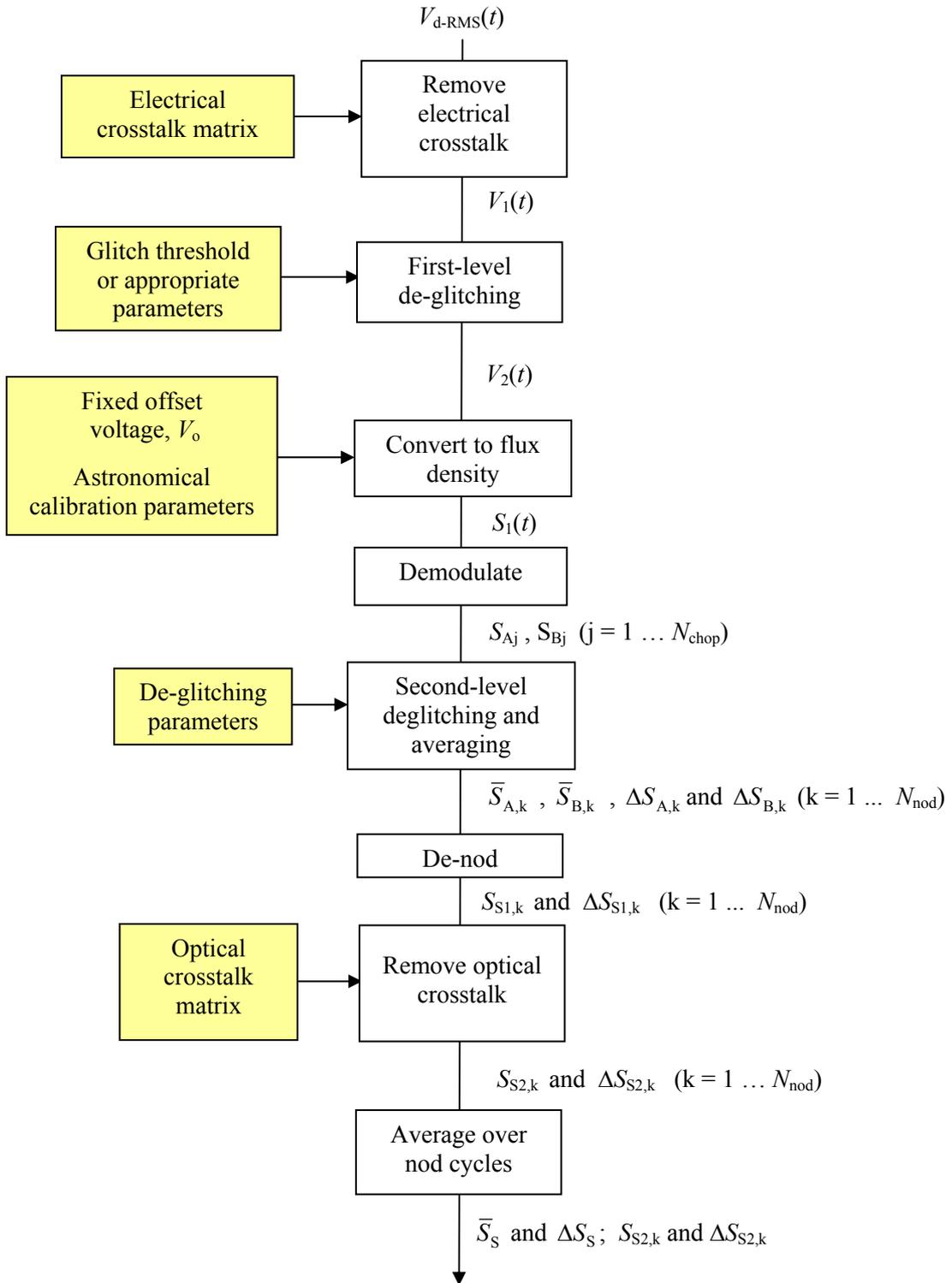


Figure 26: Pipeline block diagram for chopped/nodded observations (for **one jiggle position of one bolometer** with  $N_{chop}$  chop cycles per jiggle position).

### 6.3 Remove electrical crosstalk

This module is the same as for the scan-map pipeline (Section 5.2). The output is the crosstalk-corrected voltage timeline,  $V_{1,i}(t)$  for **bolometer**  $i$ .

### 6.4 First-level deglitching

As in the scan-map pipeline, before further processing of the measured **bolometer** voltage timeline,  $V_{1,i}(t)$ , glitches due to cosmic ray hits or other impulse-like events in the **bolometers** will be removed. The same deglitching method as used in the scan-map pipeline (Section 5.3) is adopted as the baseline, but is likely to require a different optimisation as the **bolometer** timelines in chopped mode will legitimately contain large changes between contiguous samples around the time of BSM position switching.

The output of this module is the de-glitched voltage timeline,  $V_{2,i}(t)$  for **bolometer**  $i$ .

### 6.5 Convert to flux density

The nominal method to be used to demodulate the chopped signal follows the logic outlined in Section 4.3. But because of the potentially non-linear relationship between voltage and flux density and voltage, it must be carried out in terms of flux density to ensure that the subtraction in the subsequent de-nodding step is done in the linear regime.

The voltage timelines  $V_{2,i}(t)$  are converted to flux density timelines using the same module as for the scan-map pipeline (described in Section 5.5). The reference voltage  $V_o$  and the  $K$ -values are identical.

The output of this module is a set of flux density timelines:  $S_{1,i}(t)$  for **bolometer**  $i$ .

Note that if the calibration values  $R_{d-nom}$  and  $V_o$  measured on dark sky compensate precisely the telescope background, then the first estimate of flux density produced by this module will be closely related to the sky brightness. However, to arrive at a reliable flux density estimates, the timelines must be demodulated and de-nodded.

### 6.6 Demodulate

Figure 27 (based on Figure 23) shows example **bolometer** flux density timelines, as output by the previous module, corresponding to nod positions A and B (with the source in the right beam for position A), where for simplicity the sky background is taken to be uniform.

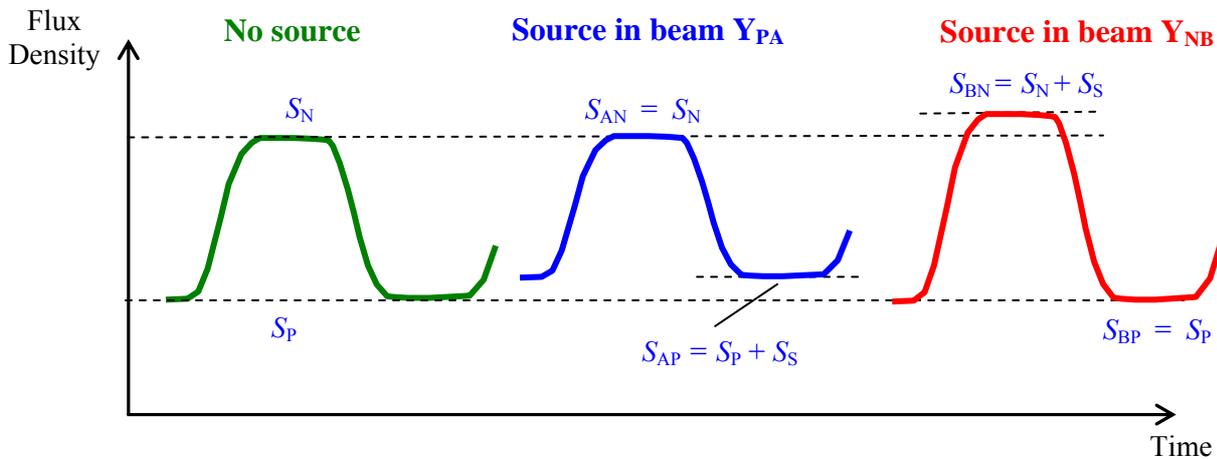


Figure 27: Example: chopped signal for nod positions A and B (assuming uniform sky background).

As drawn in Figure 27, most of the difference between the chop positions is due to the asymmetric telescope background. In nod position A, the source **decreases** the magnitude of the difference and in nod position B it **increases** it.

The demodulated flux densities for nod positions A and B are calculated as follows:

$$S_A = \bar{S}_{AP} - \bar{S}_{AN} \quad \text{and} \quad S_B = \bar{S}_{BP} - \bar{S}_{BN} \quad (54)$$

where  $\bar{S}_{AP}$ , is the average of the three (TBC) samples for the relevant half-cycle, as explained in Section 4.3, and similarly for the others.

Consider the demodulation for a given jiggle position with  $N_{\text{chop}}$  chop cycles per nod cycle and  $N_{\text{nod}}$  nod cycles. For each nod cycle, we have  $N_{\text{chop}}$  estimates of  $S_A$  and  $N_{\text{chop}}$  estimates of  $S_B$ .

The number of jiggle positions per nod position is nominally 16 for a 64-point jiggle (with 4 nod positions making up the total of 64 jiggle positions) and 7 for a seven-point. So for a nominal seven-point with one nod cycle,  $N_{\text{chop}} = 16$ . For a nominal 64-point, with 4 nod covering the 64 jiggle positions,  $N_{\text{chop}} = 4$ . For details see [3].

As the output of this module, we then have, for each jiggle position, for each nod cycle,  $N_{\text{chop}}$  estimates of  $S_A$  and likewise  $N_{\text{chop}}$  estimates of  $S_B$ :

$$S_{A,j,k} \text{ and } S_{B,j,k} \text{ where } j = 1 \dots N_{\text{chop}} \text{ and } k = 1 \dots N_{\text{nod}}.$$

Note that for most practical cases  $N_{\text{nod}} = 1$ , since the nominal jiggle map observation incorporates four nod cycles, each covering 16 different jiggle positions [3], so that there is only one nod cycle for a given jiggle position.

## 6.7 Second-level deglitching and averaging

For each nod cycle, the  $N_{\text{chop}}$  estimates of the demodulated flux densities in each of the two nod positions can now be deglitched by rejecting outliers and averaging the remaining samples, to produce mean values and an associated uncertainty.

An appropriate de-glitching scheme to employ here is median clipping, operating as follows (note that this procedure requires a minimum of five data points (always available in the case of standard SPIRE AOTs):

- (i) the median of the  $N_{\text{chop}}$  points is calculated;
- (ii) the standard deviation of the  $N_{\text{chop}}$  points is calculated, leaving out the highest and lowest values
- (iii) any points that are different from the median by more than a preset number of standard deviations (e.g., 3) are rejected;
- (iv) the process is repeated until no more outliers are identified or until there are not enough data points to continue.

The mean  $\bar{S}$  and standard error  $\Delta S$  of the de-glitched data set can then be computed in the normal way.

Note that if  $N_{\text{chop}}$  is small, then by chance the calculated uncertainty  $\Delta S$  will occasionally be inappropriately small. A minimum uncertainty per bolometer, based on the average uncertainty over the observation or based on previous observations, could be defined but this is not baselined at present. (It is already flagged in HSpot and the SPIRE Observers' Manual that any S/N values  $> 200$  should not be regarded as credible.)

For a given bolometer and jiggle position, the outputs of this module are, for each nod cycle, values of flux density and their associated uncertainties:

$$\bar{S}_{A,k}, \bar{S}_{B,k}, \Delta S_{A,k}, \Delta S_{B,k}.$$

All bolometers should be processed at this stage, even those on the sides of the arrays that are chopped out of the instrument field of view onto the instrument box during part of the observation. The ones to be rejected will be identified on the basis of PV analysis and flagged as to be ignored in the map-making.

### 6.8 De-nod

The de-nod process merely takes the difference between the flux densities in the two nod positions to derive the first estimate of the source flux density. For each of the  $N_{\text{nod}}$  nod cycles, we have:

$$S_{S1,k} = \frac{1}{2}(\bar{S}_{A,k} - \bar{S}_{B,k}) \quad \text{with} \quad \Delta S_{S1,k} = \frac{1}{2}(\Delta S_{A,k}^2 + \Delta S_{B,k}^2)^{1/2}. \quad (55)$$

The output of this module is a value of in-beam source flux density,  $S_{S1,k}$ , with an associated error  $\Delta S_{S1,k}$ , for each jiggle position of each bolometer, and for each of the  $k = 1 - N_{\text{nod}}$  nod cycles.

As noted in Section 6, if the sky background is uniform or varying linearly, it is also removed; but if there is a higher order variation in sky brightness, then it will not be completely subtracted.

### 6.9 Removal of optical crosstalk

Optical crosstalk is removed using the same method described in Section 5.8. The output of this module is then, for each jiggle position of each bolometer, and for each nod cycle, an estimate,  $S_{S2,k}$ , of the in-beam source flux density and its associated statistical uncertainty,  $\Delta S_{S2,k}$ .

Note that the crosstalk matrix elements may be different to those in the case of the scan map pipeline (Section 5.8) due to the different BSM positions. In principle a different crosstalk matrix is needed for each BSM position.

### 6.10 Average over nod cycles

If  $N_{\text{nod}} > 1$ , then a weighted mean and uncertainty can be calculated from the separate estimates:

$$\bar{S}_S = \frac{\sum_{k=1}^{N_{\text{nod}}} \frac{S_{S2,k}}{(\Delta S_{S2,k})^2}}{\sum_{k=1}^{N_{\text{nod}}} \left(\frac{1}{\Delta S_{S2,k}}\right)^2} \quad \text{and} \quad \Delta S_S = \left[ \frac{1}{\sum_{k=1}^{N_{\text{nod}}} \left(\frac{1}{\Delta S_{S2,k}}\right)^2} \right]^{1/2}. \quad (56)$$

Note: a weighted mean is only legitimate if the individual values and their uncertainties are mutually compatible. In order to avoid vulnerability to any anomalous estimates and to provide a means of identifying any such anomalies, the pipeline should therefore preserve and continue to process the results of the individual nod cycles in addition to the averaged result.

The outputs of this module are therefore, for each jiggle position of each bolometer,

- (i) the weighted average flux density  $\bar{S}_S$  and its associated uncertainty  $\Delta S_S$ ;
- (ii) for each individual nod cycle:  $S_{S2,k}$  and  $\Delta S_{S2,k}$  (i.e., just the inputs).

### 6.11 Calculation of point source flux density and positional offset (point source photometry only)

As noted in Section 6.1, in a point source observation, three bolometers on a given array provide a measurement of the source (primary, upper, and lower). Consider any one of the measurements. It will involve observations of seven BSM offset positions, with the central (0,0) position observed twice. For each

of the eight positions we have a flux density estimate and its statistical uncertainty,  $S_i \pm \Delta S_i$ , and an angular offset on the sky with respect to the nominal (0,0) pointed position,  $(\Delta\theta_{yi}, \Delta\theta_{zi})$ .

The pipeline assumes that the source is point-like and carries out a weighted fit of the eight points to a 2-D Gaussian model of the beam profile. The free parameters for the fit are the peak flux density and the Y and Z positional offsets with respect to the central position (0,0). The results are fitted flux density and offsets, and their associated uncertainties. The estimation of flux density and position are carried out independently

- for each of the  $N_{\text{nod}}$  nod cycles
- for each of the three **bolometers** (primary, upper and lower) on each array.

All of these measurements are also combined together by taking a weighted mean.

Note that:

- (i) The quality of the positional offset fit will be highly sensitive to S/N. As a rule of thumb, the S/N on the position fit is roughly equivalent to the S/N on the peak position (so for instance, a S/N of about 20 for PSW should result in an uncertainty of  $\sim 1''$  in position since the beam FWHM is close to  $20''$ ). For low S/N observations, the position fit will not be reliable. The adopted routine must therefore produce an indication of the reliability of the fit.
- (ii) In the case of low-S/N data, the fitted flux density should be essentially equivalent to the weighted sum of the eight measured points (i.e., weighted with respect to the relative beam profile response in the different positions, under the assumption of accurate pointing). This estimate should be made available for all observations (both high and low S/N).

## 7. Astronomical calibration

Conversion of the **bolometer** timelines from voltage to flux density (described in Section 5.5) incorporates that astronomical calibration through the  $K$ -parameters. This section describes how the  $K$ -parameters are to be measured using PCal to characterise the relative variation of the small signal responsivity with operating point voltage, and using an astronomical calibrator to establish the absolute scale. Corrections for partial resolution of calibration sources by the SPIRE beam are also described, and the method of conversion of the quoted in-beam flux density to a different assumed source spectral index is outlined. Further details and computation of the relevant calibration file parameters are given in [8].

### 7.1 Assumptions

1. The absorbed **bolometer** power is proportional to the flux density at the aperture. The quantity that is directly proportional to absorbed **bolometer** power is the integral over the band of the flux density weighted by the instrument relative spectral response function (RSRF),  $R(\nu)$ :

$$\bar{S} = \frac{\int_{Passband} S(\nu)R(\nu) d\nu}{\int_{Passband} R(\nu) d\nu}$$

where  $S(\nu)$  represents the source flux density at the telescope aperture and  $R(\nu)$  is the instrument Relative Spectral Response Function (RSRF). Derivation of a monochromatic flux density requires definition of a standard frequency for the band and some assumption about the shape of the source spectrum.

2. The power radiated by PCal for a given applied excitation is constant.
3. The signal from PCal is small enough that the responsivity can be taken as the same with PCal on and PCal off – i.e., the PCal response is directly proportional to the small-signal responsivity at the operating point.

### 7.2 Determination of the $K$ -parameters

The response,  $\Delta V_p$  to a standard PCal flash is measured as a function of operating point voltage,  $V$  (nominally by operating PCal with the telescope viewing a selection of sources of different brightness). It is not necessary to know how bright all the sources are – they are just being used to establish a range of backgrounds on the **bolometers**. The effect of a bright source on the responsivity can also be simulated by raising the bolometer bath temperature – **this is not currently the baseline plan but could be considered at a future time**. The characterisation of the responsivity as a function of operating point voltage using PCal is not model-dependent or sensitive to the bolometer or instrument temperatures that occur during the calibration measurements. The signal from a faint source observed with a certain operating point voltage can also be converted to any other operating point voltage.

The inverse of the PCal response is directly proportional to  $f(V)$ :

$$\frac{1}{\Delta V_p(V)} = Af(V), \quad (57)$$

where  $A$  is a constant.

A graph of  $\frac{1}{\Delta V_p(V)}$  against  $V$  is thus a scaled version of the graph of  $f(V)$  vs.  $V$ , (Figure 22) which is the function that we need to know for flux density calibration. The constant of proportionality,  $A$ , can be found from an observation of a known astronomical source as follows. Consider an observation of a calibration source of flux density  $\bar{S}_{\text{Calib}}$  for which the voltage recorded off-source is  $V_{\text{off}}$  and the voltage recorded on-source is  $V_{\text{on}}$ . We then have

$$\bar{S}_{\text{Calib}} = \int_{V_{\text{off}}}^{V_{\text{on}}} f(V) dV = \frac{1}{A} \int_{V_{\text{off}}}^{V_{\text{on}}} \left[ \frac{1}{\Delta V_p(V)} \right] dV . \quad (58)$$

Since  $\bar{S}_{\text{Calib}}$  is known and the integral can be evaluated from the PCal response data, the constant  $A$  can be found and a graph of  $f(V)$  vs.  $V$  determined. The  $K$ -parameters can then be fitted to this graph.

Note that:

- (i) the astronomical calibration observation does not have to be made with the off-source operating point voltage equal to  $V_0$  or any other particular value;
- (ii) the calibration observation does not need to be on a faint source.

Ideally this calibration procedure would involve mapping a calibration source with every bolometer in order to derive the absolute  $K$  parameters, but this will not be practical in a reasonable amount of time. An alternative approach is therefore proposed as follows:

1. observations of an absolute calibrator with a subset of bolometers can be used to establish the overall absolute scale factors for those bolometers;
2. scanning observations of reasonably bright sources can be used to measure the relative gains of the all bolometers with high accuracy, allowing the absolute gains of the subset to be transferred to all bolometers. Extended and complex source structure may bring a speed advantage over a single point-like calibration source.

### 7.3 Calculation of source flux density

The above analysis relies on proportionality between flux density and power. As noted in Section 5.5, the quantity that is directly proportional to absorbed **bolometer** power is the integral over the band of the flux density weighted by the instrument RSRF. The calibrator source flux density in equation (58) is

$$\bar{S}_{\text{Calib}} = K_{\text{Beam}} \frac{\int_{\text{Passband}} S_C(\nu) R(\nu) d\nu}{\int_{\text{Passband}} R(\nu) d\nu} , \quad (59)$$

where  $S_C(\nu)$  represents the calibrator flux density (taking no account of the beam size) and  $K_{\text{Beam}}$  is a correction factor for partial resolution of the calibrator, and takes into account the fact that the calibrator is not necessarily a point source.  $K_{\text{Beam}}$  is unity for a point source, and is slightly less than one for the SPIRE primary calibration source, Neptune (see Section 7.4).  $\bar{S}_{\text{Calib}}$  can thus be found from a knowledge of the RSRF and the calibrator spectrum at the epoch of its observation.

Likewise, if a source with spectrum  $S_S(\nu)$  is observed, the measured **in-beam** flux density is given by

$$\bar{S}_S = \frac{\int_{Passband} S_S(\nu) R(\nu) d\nu}{\int_{Passband} R(\nu) d\nu}. \quad (60)$$

In processing the data from an (unknown) source, the automatic pipeline must make some assumption concerning the source spectrum in order to derive a result in terms of flux density. The simplest approach is to assume that the spectrum is a power law across the band defined by an index  $\alpha_S$ :

$$S_S(\nu) = S_S(\nu_0) \left( \frac{\nu}{\nu_0} \right)^{\alpha_S}, \quad (61)$$

where we can choose  $\nu_0$  to be some suitable frequency within the band – for instance at or near the band centres (corresponding  $\lambda_0 = 250, 350, 500 \mu\text{m}$ ) for the three photometer bands. The observer may wish to adopt a different assumed source spectrum (e.g., based on a multi-wavelength data-set including SPIRE only or SPIRE plus other measurements such as PACS and/or ground-based observations). The relevant corrections are given in Section 7.4.

The measured flux density (equation 60) is

$$\bar{S}_S = \frac{S_S(\nu_0)}{\nu_0^{\alpha_S}} \left[ \frac{\int_{Passband} \nu^{\alpha_S} R(\nu) d\nu}{\int_{Passband} R(\nu) d\nu} \right]. \quad (62)$$

The flux density at frequency  $\nu_0$ , which will be the final version to be quoted to the observer, is therefore given by:

$$S_S(\nu_0) = \bar{S}_S \left[ \frac{\nu_0^{\alpha_S} \int_{Passband} R(\nu) d\nu}{\int_{Passband} \nu^{\alpha_S} R(\nu) d\nu} \right] = K_4 \bar{S}_S. \quad (63)$$

The measured flux density (as computed using equation 62) must therefore be multiplied by  $K_4$  to derive the monochromatic flux density at the standard wavelength (to be quoted to the user). The convention to be used for SPIRE and PACS is to adopt  $\alpha_S = \alpha_{S_0} = -1$  (corresponding to  $\nu S_\nu$  flat across the band), so that:

$$K_4 = \frac{\int_{\text{Passband}} R(\nu) d\nu}{\nu_0 \int_{\text{Passband}} \frac{R(\nu)}{\nu} d\nu}. \quad (64)$$

For  $\alpha_{s_0} = -1$ , the currently adopted photometer RSRFs [9], and  $\lambda_0 = 250, 350, 500 \mu\text{m}$ ,  $K_4 = (0.9939, 0.9898, 0.9773)$  for the (PSW, PMW, PLW) bands. In practice, the parameter  $K_4$  will be incorporated into the adopted values of  $K_1$  and  $K_2$  (see Section 5.5).

#### 7.4 Beam correction factor

The primary calibration sources for SPIRE, Uranus and Neptune, have typical angular diameters of  $1.8''$  and  $1.1''$  respectively. We calculate the corresponding small correction factors for partial resolution of the disk by the beam assuming a Gaussian beam profile coupling to a uniformly bright planetary disk. The corresponding beam correction factor is given by [10]:

$$K_{\text{Beam}}(r_C, \theta_{\text{Beam}}) = \frac{1 - \exp\left(-\frac{4\ln(2)r_C^2}{\theta_{\text{Beam}}^2}\right)}{\frac{4\ln(2)r_C^2}{\theta_{\text{Beam}}^2}}, \quad (65)$$

where  $r_C$  is the angular radius of the planet and  $\theta_{\text{Beam}}$  is the beam FWHM. The values of  $K_{\text{Beam}}$  for typical calibrator angular sizes and the predicted FWHM beamwidths, are summarised in Table 4.

Band		PSW	PMW	PLW
$\theta_{\text{Beam}}$ (")		18	25	36
<b><math>K_{\text{Beam}}</math></b>				
Neptune				
$r_C = 1.10''$	min	0.9948	0.9973	0.9987
$1.135''$	average	0.9945	0.9971	0.9986
$1.17''$	max	0.9942	0.9970	0.9985
Uranus				
$r_C = 1.65''$	min	0.9884	0.9940	0.9971
$1.74''$	average	0.9872	0.9933	0.9968
$1.83''$	max	0.9858	0.9926	0.9964

Table 4: Nominal beam correction factors for Uranus and Neptune

The values of  $K_{\text{Beam}}$  for Uranus and Neptune, and for the larger asteroids, will be computed and tabulated as a function of time during the mission so that the appropriate values can be interpolated for an observation of a given calibrator on a given day.

#### 7.5 Conversion of measured flux densities to a different source spectral index (colour correction)

As discussed above, all results will be calculated and quoted under the assumption that the source has a spectrum with  $\nu S_\nu$  flat across the band ( $\alpha_{s_0} = -1$ ). This will not be the case for most observations, and a correction will need to be applied by the astronomer based on other information (for instance, measurements

in other SPIRE or PACS bands and/or data from other telescopes).

Assume that the source spectrum actually follows a power law with a different spectral index  $\alpha_{\text{Snew}}$ . Let  $S'_S(\nu_0)$  be the source flux density at  $\nu_0$  for that spectral shape. We then have from equation (63),

$$S'_S(\nu_0) = \nu_0^{(\alpha_{\text{Snew}} - \alpha_{\text{So}})} \left[ \frac{\int_{\text{Passband}} R(\nu) \nu^{\alpha_{\text{So}}} d\nu}{\int_{\text{Passband}} R(\nu) \nu^{\alpha_{\text{Snew}}} d\nu} \right] S_S(\nu_0) = K_C(\alpha_{\text{Snew}}) S_S(\nu_0). \quad (66)$$

The correction factor,  $K_C$ , can easily be computed and tabulated for various values of  $\alpha_{\text{Snew}}$ , so that the astronomer can implement a straightforward multiplicative correction factor corresponding to the chosen spectral index. Figure 28 shows  $K_C$  vs. adopted source spectral index for the currently assumed photometer filter profiles, taking  $\alpha_{\text{So}} = -1$  (the filter profiles will be updated in the near future, but not such as to change these curves significantly). Typical SPIRE sources will have  $\alpha_S$  in the range 0 – 3, requiring corrections up to a few %.

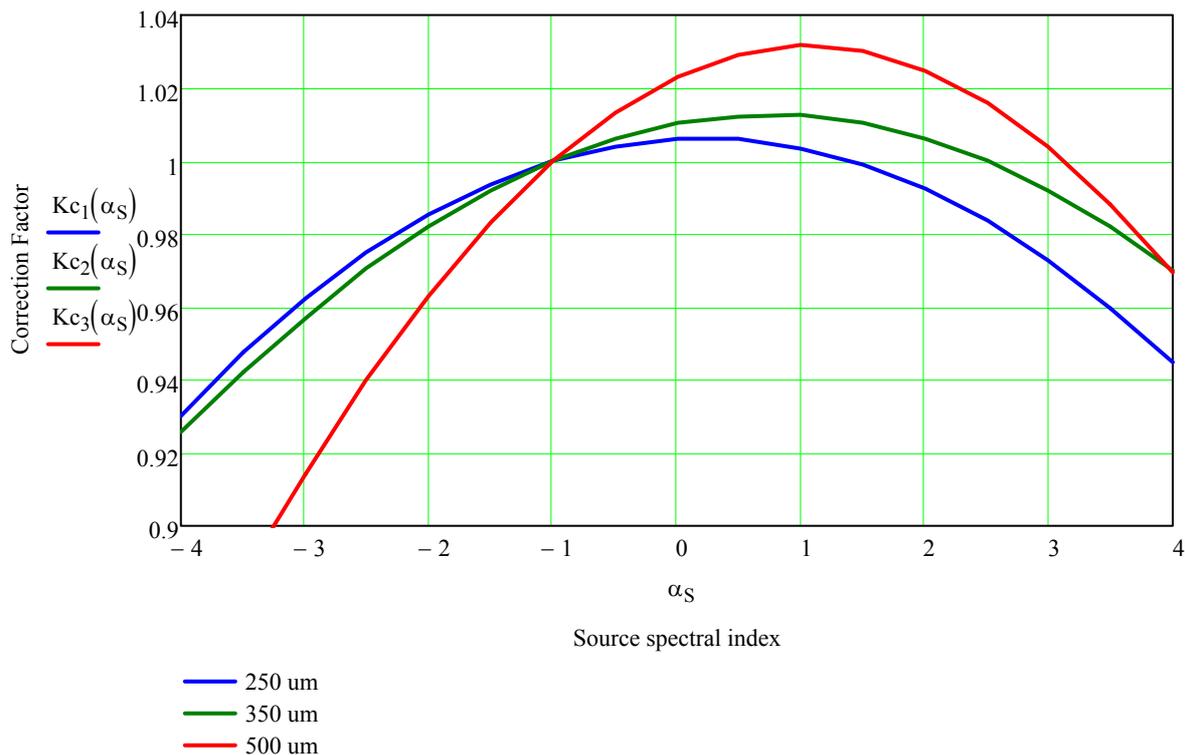


Figure 28: Spectral index correction factor,  $K_C$ , vs. true source spectral index for the currently assumed SPIRE filter bands and  $\alpha_{\text{So}} = -1$ .

Note that it is equally straightforward to convert the results to some other wavelength if that is desired. Sometimes it is the practice to quote the measured flux density at a flux-weighted effective wavelength, to take into account the fact that the measurement is biased towards one side of the band in the case of a source with a steep spectrum. We propose not to adopt this practice here for two reasons:

- (i) it is no more accurate or correct than the scheme described above;

- (ii) we can avoid complication and potential confusion by selecting a standard set of wavelengths for all measurements.

## 8. References

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