PACS Test Analysis Report FM-ILT - Part II

The PACS ICC
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Chapter 1

Spectrometer

1.1 Spectrometer Module level
Req. 1.2.1.2.17 Optimum detector bias and temperature settings for Ge:Ga detectors, time constant: bias change spectrometer

1.2.1.2.17 - A. History

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<td>Jürgen Schreiber, Ulrich Klaas, Helmut Dannerbauer, Markus Nielbock, Jeroen Bouwman</td>
<td>First issue</td>
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1.2.1.2.17 - B. Summary

- The minimum NEP, and therefore the corresponding optimum bias, is reached between 60 and 70 mV bias voltage for the red array and between 139 and 199 mV for the blue array, which is slightly lower than found at module level tests.

- The mean NEP of the blue array shows a slight trend to decrease with rising detector temperature between 2.1 and 2.9 K.

- The median responsivity of the red array is 37.78 A/W, while the median NEP amounts to $8.9 \times 10^{-18} \, WHz^{-1/2}$. The median responsivity of the blue array is 11.45 A/W, while the median NEP amounts to $2.07 \times 10^{-17} \, WHz^{-1/2}$.

- Some additional pixels than the already known bad pixels show an extraordinarily deviating NEP behaviour and are identified.

- For some bias steps a signal transient behaviour was found with decay times between 1/2 to 4 minutes. The recommendation is therefore to insert wait times of about 8 minutes, should a bias change be necessary.
1.2.1_2.17 - C. Data Reference Sheet

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1.2.1.2.17 - D. Test Description

1.2.1.2.17 - D.1. Introduction

The goal of this test is to find the optimum bias voltage at which the Ge:Ga detectors work stable (e.g. do not show spiking pixels) and the NEP shows a minimum. Additionally, the optimum temperature of the blue detector array should be determined with respect to a minimum NEP and any transient effects on the signal after a bias change should be investigated. The obtained data also allows to determine the NEP and the responsivity of each pixel. The resulting values should be compared to the corresponding values of the module level tests.

1.2.1.2.17 - D.2. Test Overview

The bias scans were carried out on 28 February 2007 yielding two valid telemetry files. FILT_OptBias_058_01.tm contains the bias scan for the red detector array, while FILT_OverNightBatch_20070228_02.tm contains the bias and temperature scan of the blue detector array. Differential measurements were performed using both OGSE blackbodys as sources of radiation and the OGSE chopper wheel to chop between both sources. For the red array the BB temperatures were chosen as 25.3 K and 24.7 K while the settings were 32.75 K and 31.25 K for the blue array. The mean of these temperatures provide a similar flux as expected from the telescope. The chopper wheel rotation frequency was set to 125 mHz, the measurement interval for each bias voltage was 180 s resulting in about 22 signal- and chopper cycles per bias voltage (see Fig. 1.1). The clearly visible signal transient effect after bias changes in Fig. 1.1 hampers the calculation of the signal differences. The smallest capacitance of 0.14 pF (effective) was used. Data acquisition was done in default mode, that means averaging 32 ramp readouts in 1/2 s ramps. Consequently, this results in 4 samples per ramp that were fitted linearly to get the signal in readouts per second (see Fig. 1.4). The whole 16 bit ADC range corresponds to 6.26 V. For the red array we scanned through a bias voltage range between 20 and 90 mV in steps of 10 mV (see Fig.1.2), while for the blue array a range between 80 and 290 mV in steps of 30 mV was sampled (see Fig.1.3). The temperature range of the blue detector array was scanned between 2.1 K and 2.9 K in steps of 0.2 K (see Fig.1.3), while the red detector had a constant temperature of 1.8 K. The grating position was set always to 461000 which corresponds to a wavelength of 184 μm for the center of the red array and 92 μm for the center of the blue array (the long wavelength channel order sorting filter was used) by applying the FM_1.0 wavelength calibration file. The corresponding flux on a pixel is calculated using the recent instrument model of A.P. coded in PCSS by M.G. The flux values of different OGSE BB temperatures available in the document RD-6 were scaled to the actual used BB temperatures. This results in a differential flux of $3.283 \times 10^{-16}$ W at an absolute flux of $4.3443 \times 10^{-15}$ W per pixel for the red array, and $2.502 \times 10^{-15}$ W at an absolute flux of $1.213 \times 10^{-14}$ W per pixel for the blue array.

The open and dummy channels (at a checkout voltage of 10 mV) and the following already known dead pixels were not considered in calculations for the red array: [11,3], [11,5], [10, 19], [5, 22], and for the blue array: [6, 15], [3, 16], [5, 22], [2, 23], [9, 24]. Since the bias steps were equal over the tested bias range, the relative bias increase decreases with higher bias values.
Figure 1.1: Example of the signal cycles for one bias voltage setting.

Figure 1.2: Signals, signal uncertainties from fit error and bias voltage overplotted for a red pixel. Formally, the bias voltage is negative.
Figure 1.3: Signals, signal uncertainties from fit error and bias voltage overplotted for a blue pixel. Formally, the bias voltage is negative. The five "step periods" correspond to the five different temperature settings between 2.1 and 2.9 K in steps of 0.2 K.
1.2.1_2.17 - E. Results

We checked for a few examples the signal consistency of raw ramps and on-board processed ramps reduced to 4 samples per ramp, with very good agreement (see Fig.1.4).

![Graphs showing raw and averaged ramps](image)

Figure 1.4: Linearly fitted raw (left panels) and default averaged ramps (right panels) of the same red and blue pixel at the same reset. Note the agreement of the fit results (slope).

1.2.1_2.17 - E.1. Optimum Bias Voltage

In Fig. 1.5 the mean and median NEP of all pixels of the red array is plotted versus the bias voltage. The error bars are the calculated standard deviation of the NEP over all pixels, hence reflect the dispersion. The minimum of the mean and median NEP is at a bias voltage of 70 mV, where also the dispersion shows a minimum. The achieved NEPs at 60 mV and 70 mV bias voltage are not very different and the dispersion of the 60 mV NEPs covers the whole range of the 70 mV bias setting. Consequently, the whole bias range between 60 mV and 70 mV can be considered as optimum bias voltage.
The mean and median NEP of the blue array and their dependence on the bias voltage are plotted in Fig. 1.6. The dependence on the detector temperature is obviously very small, except for the smallest and highest applied bias voltage.

The minimum of the mean and median NEP is at a bias voltage of 169 mV (measured housekeeping value while 170 mV were commanded). The achieved NEPs at 139, 169 and 199 mV are not very different and the error bars are comparably large. Consequently, the whole bias range between 139 and 199 mV can be considered as optimum bias voltage.

In Fig. 1.7 the temperature dependence of the NEP of the blue array at 170 mV bias voltage is shown. The median NEP does not show any trend with the detector temperature. The mean NEP shows a slight tendency to decrease with increasing detector temperature. Since the shimming of the blue detector temperature heater was such, that for temperatures above 2.5 K the heat dissipation exceeded the allowed limit, all subsequent Ge:Ga detector operation during FM-ILT was restricted to 2.5 K, although 2.9 K would result in a slightly lower NEP. RD-9 reported a somewhat higher risk of spiking pixels at high bias voltage for the higher temperatures. Before the final instrument delivery the heater shimming was adjusted, so that now also 2.9 K permanent operation do not violate the thermal budget.
Figure 1.6: Mean (left panel) and median (right panel) NEP (including standard deviation as error bars) vs. bias voltage for the blue array and dependent on the detector temperature.

Figure 1.7: Mean (left panel) and median (right panel) NEP vs. detector temperature at the optimum bias voltage of 169 mV.
1.2.1_2.17 - E.2. Responsivity and NEP at Optimum Bias Voltage

In Fig. 1.8 the resulting responsivities of the whole red array at 70 mV are displayed except for the open and dummy channels. The 4 known dead pixels and the 2 array low response pixels ([12, 1], [7, 12], see RD-8) show up in black. The boarder modules at y-position 4, 9, 14, 24 (x-direction is defined from top to bottom, y-direction from left to right) show up darker (i.e. with lower responsivity values) than the average of the other modules. This is very likely due to a remaining mis-alignment which leads to a reduced flux falling onto these boarder modules, thus the calculation yields lower values than the actual intrinsic responsivity. There are three additional modules that show up with lower responsivities than the average, which is module 6, 20 and 21.

In Fig. 1.9 the resulting NEPs of the whole red array at 70 mV are displayed except for the open and dummy channels. The 4 known dead pixels show up in black, while the 2 known low response pixels ([12, 1], [7, 12], see RD-8) show up with high NEPs. But there are 2 more conspicuous pixels with high NEPs at the positions [11, 2] and [16, 2] which did not show up as such at module level tests. The boarder modules at y-position 4, 9, 14, 24 show on average higher NEP values than the other modules. This is very likely due to a remaining mis-alignment which leads to a reduced flux falling onto these boarder modules. Since this reduced flux is not taken into account in the NEP calculation, this artificially increases the NEP values. There is perfect agreement with the results of the NEP-measure of the corresponding FM-ILT/IST test (see RD-7).

The median responsivity of the red array is 37.78 A/W and the median NEP amounts to $8.9 \times 10^{-18}\, WHz^{-1/2}$. Both values are slightly lower than found at module level tests (resp.: 30 to 90 A/W, NEP: $1\ldots2 \times 10^{-17}\, WHz^{-1/2}$) but still in good agreement considering the large array variations, uncertainties in flux determination, and possibly the different used spectral ranges (see RD-8). The applied wavelength range during the corresponding module level tests is not obvious from document RD-8, but is probably different from the one used at FM-ILT.

In Fig. 1.10 the resulting responsivity of the whole blue array at 169 mV are displayed except for the open and dummy channels. The 4 known dead pixels show up in black. Additionally, pixel [9, 24] has a very low responsivity, what was not the case during module level tests. It was detected as a new dead pixel already in a corresponding FM-ILT/IST test (see RD-7). The boarder modules at y-position 4, 9, 14, 24 show up darker (i.e. with lower responsivity values) than the average of the other modules. This is very likely due to a remaining mis-alignment which leads to a reduced flux falling onto these boarder modules, thus faking reduced responsivities.

In Fig. 1.11 the resulting NEPs of the whole blue array at 169 mV bias voltage are displayed except for the open and dummy channels. The 4 known dead pixels show up in black, in addition the recently found dead pixel [9, 24]. In the blue array all boarder modules at y-position 4, 9, 14, 19 except for module 24 are affected by poor alignment and show up brighter than the other modules. Additionally, there are some conspicuous pixels showing up exceedingly bright, i.e. with high NEP values in the left-most module 0, module 8 and in module 23. Also the pixels [1, 19] and [6, 16] show up extraordinarily bright. There is perfect agreement with the results of the NEP-measure of the corresponding FM-ILT/IST test except for module 24 (see RD-7). This module, especially a few pixels at the top seem to have had higher NEPs at IST tests than found here.

The median responsivity of the blue array is 11.45 A/W and the median NEP amounts to $2.07 \times 10^{-17}\, WHz^{-1/2}$. The responsivity is about two times higher and the NEP is about 5 times lower compared to the results found at module level tests (see RD-9). The reason for this disagreement is probably the different mean wavelength which was 60 µm at module level tests compared to 92 µm here and the uncertainties in the determination of the absolute flux on the detector.
Figure 1.8: Responsivity [A/W] at optimum bias voltage for the red array.

Figure 1.9: NEP (in units of $10^{-17} W/\sqrt{Hz}$) at optimum bias voltage for the red array.
Figure 1.10: Responsivity [A/W] at optimum bias voltage and at a detector temperature of 2.5 K for the blue array.

Figure 1.11: NEP (in units of $10^{-17} W/\sqrt{Hz}$) at optimum bias voltage and at a detector temperature of 2.5 K for the blue array.
1.2.1_2_17 - E.3. Signal Transient Behaviour after Bias Change

In order to estimate the stabilisation times of the signals after a bias change we fitted the signal time series smoothed with a median boxcar filter after each change of the bias setting. We distinguished the signals related to each OGSE BB and the corresponding differential signal. We used an exponential fit function after subtracting the mean signal of the last few signal modulations of the plateaux considered as stabilised (see fit examples in Fig. 1.12). Practically, a linear fit was applied to the logarithm of the signal values. Therefore, the exponential function is offset-free, but has a multiplicative offset as free fit parameter. The other free fit parameter was the decay time of the exponential function.

The resulting median exponential decay times of all pixels of the red array and the blue array are depicted in Figs. 1.13 and 1.14, respectively. The error bars correspond to the dispersion of the decay times over all pixels. The corresponding resulting median multiplicative factor of all pixels are depicted on the panels at the right hand side, where the error bars indicate the standard deviation.

The decay times of the differential signals of the red array are very high (longer than 10 minutes) and the offsets are not significant for all bias steps (see Fig. 1.13). The decay times are not significant since there are very large error bars that span beyond zero seconds. The conclusion is that the differential signal does show either no or only very small transient behaviour below the noise level of the signal. The decay times of the OGSE BB1/2 signals of the red array are not significant for all bias voltages except at 60, 70 and 80 mV (at least for OGSE BB2). Comparing the OGSE BB1/2 decay times and offsets the results for all biases are rather reproducible. There is a minimum significant decay time of about 2 minutes around the found optimum bias voltage between 60 and 70 mV. The decay times for the other bias voltage steps rise to more than 10 minutes, if at all real.

The decay times and offsets of the differential signals of the blue array are not significant for all bias steps except for the smallest voltage of 80 mV (see Fig. 1.14). The decay times are not significant since there are very large error bars that span beyond zero seconds. The conclusion is that the differential signal does show either no or only very small transient behaviour below the noise level of the signal. The decay times of the OGSE BB1/2 signals of the blue array are not significant for all bias voltages except at 80, 110 (at least for OGSE BB1), 200 (at least for OGSE BB2), 230 and 260 mV. Comparing the OGSE BB1/2 decay times and offsets the results for all biases are rather reproducible. There is a significant local minimum of decay times of about 90 s at 260 mV bias voltage. The offsets show that the signal is decreasing with time down to the final plateau value. The smallest decay time of about 40 s is found at the smallest bias of 80 mV. The offset shows that here the signal rises with time up to the final plateau value. The decay times at the other bias voltage steps rise to more than 10 minutes but for these biases the transient behaviour is statistically not significant. The multiplicative offset is negative for the smallest bias and changes to positive values for the highest biases. In the scope of this discussion it has to be considered that the relative bias steps are decreasing with higher bias voltages! The step to the first bias plateau should be the largest if it starts from zero!

Comparison with FM-ILT/IST bias scan (see Figs. 7 and 8 in RD-7): Overall there is good agreement of the results for both arrays. The decay times show similar dependencies on the bias voltages and the absolute values are also similar except for the smallest bias of the red array. The short significant decay time at 20 mV bias found at the IST cannot be confirmed here. The reason could be that the start conditions of the bias setup were different!

Significant decay times of the red array span a range between 2 and 4 minutes. Significant decay times of the blue array span a range between 1/2 minute and 3 minutes. Therefore, we recommend to include a wait time of about 8 minutes after each bias change before restarting data acquisition.
Figure 1.12: Examples of exponential fits to the smoothed signal time series after a bias change. Upper left panel: OGSE BB1 red detector signal (positive chopper plateaux); upper right panel: OGSE BB2 red detector signal (negative chopper plateaux); central left panel: Red detector differential signal; central right panel: OGSE BB1 blue detector signal (positive chopper plateaux); lower left panel: OGSE BB2 blue detector signal (negative chopper plateaux); lower right panel: Blue differential signal.
Figure 1.13: Resulting exponential decay times after bias changes for the red array. Upper left panel: Decay times of OGSE BB1 signals (positive plateaux); upper right panel: Corresponding offset factors; central left panel: Decay times of OGSE BB2 signals (negative plateaux); central right panel: Corresponding offset factors; lower left panel: Decay times of differential signals; lower right panel: corresponding offset factors. Note, the first bias step is from 0 to the start bias value, all subsequent steps are between the previously set and the indicated bias voltage.
Figure 1.14: Resulting exponential decay times after bias changes for the blue array. Upper left panel: Decay times of OGSE BB1 signals (positive plateaux); upper right panel: Corresponding offset factors; central left panel: Decay times of OGSE BB2 signals (negative plateaux); central right panel: Corresponding offset factors; lower left panel: Decay times of differential signals; lower right panel: Corresponding offset factors. Note, the first bias step is from 0 to the start bias value, all subsequent steps are between the previously set and the indicated bias voltage.
1.2.1_2.17 - F. Conclusions

- The bias scan tests were carried out successfully and allow a verification of the optimum bias setting for both arrays under laboratory conditions.
- The minimum NEP and therefore the optimum bias is reached between 60 and 70 mV bias voltage for the red array and 139 and 199 mV for the blue array. This result differs from the bias of minimum NEP found in the module level tests, where slightly higher optimum bias voltages were established (which was between 70 and 80 mV for the red array (see RD-8) and around 200 mV for the blue array (see RD-7)).
- There is a very weak trend towards lower NEP with higher detector temperature for the blue array for the range 2.1 - 2.9 K.
- Some more pixels than the already known bad pixels show deviating and extraordinarily high NEP behaviour. Future tests of this kind should provide a check whether the number of affected pixels remains stable.
- Estimates of the absolute responsivities and NEPs at the optimum bias could be established for each pixel.
- For some bias steps a transient behaviour was found with decay times between 1/2 to 4 minutes. Therefore, wait times of about 8 minutes after a bias change are recommended.

1.2.1_2.17 - G. IA scripts used / remarks on PCSS

CAP_1.2.1_real_red.py
CAP_1.2.1_real_blue.py
spg java function fitRamps() to fit all default mode ramps.

1.2.1_2.17 - H. Lessons learned for IMT/IST/PV

The measurement time after the bias changes should be extended from 2 minutes to about 8 minutes (if possible) to be sure to reach a stable signal plateau. This would also allow a more accurate determination of the transient behaviour.
The right-most modules at the boarder of the field of view seem to receive less radiation than the others. It is known that the alignment was not completely perfect by the repair done before ILT period 2. Another alignment improvement was done after ILT period 2, so that changes are expected for the upcoming IST tests. The optimum bias voltages apply for laboratory conditions with no ionising radiation. In-orbit operation with lower bias voltages will be very likely, since ionising radiation leads to considerably higher responsivity values but also a much higher likelihood of spiking for the now found optimum bias voltages. Also frequent curing to hold the responsivity values on a reasonable level and thus prohibit spiking can be considered.
1.2.1.2_17 - I. Appendix

1.2.1.2_17 - I.1. Plots of responsivity vs. bias voltage for individual modules

Figure 1.15: Responsivities vs. bias of red modules 0 to 5.
Figure 1.16: Responsivities vs. bias of red modules 6 to 11.
Figure 1.17: Responsivities vs. bias of red modules 12 to 17.
Figure 1.18: Responsivities vs. bias of red modules 18 to 23.
Figure 1.19: Responsivities vs. bias of red module 24.
Figure 1.20: Responsivities vs. bias of blue modules 0 to 5 at a det. temperature of 2.5 K.
Figure 1.21: Responsivities vs. bias of blue modules 6 to 11 at a detector temperature of 2.5 K.
Figure 1.22: Responsivities vs. bias of blue modules 12 to 17 at a det. temperature of 2.5 K.
Figure 1.23: Responsivies vs. bias of blue modules 18 to 23 at a det. temperature of 2.5 K.
Figure 1.24: Responsivities vs. bias of blue module 24 at a det. temperature of 2.5 K.
1.2.1_2_17 - I.2. Plots of NEP vs. bias voltage for each pixel

The known dead pixels are not considered and discarded!

Figure 1.25: NEP vs. bias of red module 0
Figure 1.26: NEP vs. bias of red module 1
Figure 1.27: NEP vs. bias of red module 2
Figure 1.28: NEP vs. bias of red module 3
Figure 1.29: NEP vs. bias of red module 4
Figure 1.30: NEP vs. bias of red module 5
Figure 1.31: NEP vs. bias of red module 6
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Figure 1.36: NEP vs. bias of red module 11
Figure 1.37: NEP vs. bias of red module 12
Figure 1.38: NEP vs. bias of red module 13
Figure 1.39: NEP vs. bias of red module 14
Figure 1.40: NEP vs. bias of red module 15
Figure 1.41: NEP vs. bias of red module 16
Figure 1.42: NEP vs. bias of red module 17
Figure 1.43: NEP vs. bias of red module 18
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Figure 1.45: NEP vs. bias of red module 20
Figure 1.46: NEP vs. bias of red module 21
Figure 1.47: NEP vs. bias of red module 22
Figure 1.48: NEP vs. bias of red module 23
Figure 1.49: NEP vs. bias of red module 24
Figure 1.50: NEP vs. bias of blue module 0 at a det. temperature of 2.5 K
Figure 1.51: NEP vs. bias of blue module 1 at a det. temperature of 2.5 K
Figure 1.52: NEP vs. bias of blue module 2 at a det. temperature of 2.5 K
Figure 1.53: NEP vs. bias of blue module 3 at a det. temperature of 2.5 K
Figure 1.54: NEP vs. bias of blue module 4 at a det. temperature of 2.5 K
Figure 1.55: NEP vs. bias of blue module 5 at a det. temperature of 2.5 K
Figure 1.56: NEP vs. bias of blue module 6 at a det. temperature of 2.5 K
Figure 1.57: NEP vs. bias of blue module 7 at a det. temperature of 2.5 K
Figure 1.58: NEP vs. bias of blue module 8 at a det. temperature of 2.5 K
Figure 1.59: NEP vs. bias of blue module 9 at a det. temperature of 2.5 K
Figure 1.60: NEP vs. bias of blue module 10 at a det. temperature of 2.5 K
Figure 1.61: NEP vs. bias of blue module 11 at a det. temperature of 2.5 K
Figure 1.62: NEP vs. bias of blue module 12 at a det. temperature of 2.5 K
Figure 1.63: NEP vs. bias of blue module 13 at a det. temperature of 2.5 K
Figure 1.64: NEP vs. bias of blue module 14 at a det. temperature of 2.5 K
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Figure 1.66: NEP vs. bias of blue module 16 at a det. temperature of 2.5 K
Figure 1.67: NEP vs. bias of blue module 17 at a det. temperature of 2.5 K
Figure 1.68: NEP vs. bias of blue module 18 at a det. temperature of 2.5 K
Figure 1.69: NEP vs. bias of blue module 19 at a det. temperature of 2.5 K
Figure 1.70: NEP vs. bias of blue module 20 at a det. temperature of 2.5 K
Figure 1.71: NEP vs. bias of blue module 21 at a det. temperature of 2.5 K
Figure 1.72: NEP vs. bias of blue module 22 at a det. temperature of 2.5 K
Figure 1.73: NEP vs. bias of blue module 23 at a det. temperature of 2.5 K
Figure 1.74: NEP vs. bias of blue module 24 at a det. temperature of 2.5 K
Req. 1.2.6 Dark Current of Ge:Ga detectors

1.2.6 - A. History

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1.2.6 - B. Summary

- The derived dark currents of the red array exceed the specifications by a factor of 2 to 5. The values are in good agreement with those found at module level tests. Stray light due to non-optimal alignment of the image slicer may effect some boarder modules.

- The derived dark current of the blue array is very low and fulfills the specifications. The values are in good agreement with those found at module level tests, but twice as high as those derived from the FM-ILT/IST tests.

- Cross-talk from the resistor channel is found in both arrays.

- On average, the dark current of supply group 3 and 1 modules is slightly lower than the dark current of the supply group 4 and 2 modules.

- The derived band gap energy of the blue array is about 10 meV with low pixel-to-pixel dispersion, which is in good agreement with the results of the module level tests. Few pixels, especially in module 0, seem to be under higher stress than the average.

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<td>RD-6</td>
<td>10/08/06</td>
<td>Cold Performance Tests on FM High Stress</td>
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<td>Ge:Ga Detector Modules, PACS-ME-TR-063</td>
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<td>RD-7</td>
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<td>RD-9</td>
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<td>Dark Current of Ge:Ga detectors from FM-ILT/IST. IMT_502, PACS-MA-TR-26</td>
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<td>Req. 1.2.1.2.17 Optimum detector bias and temperature settings, for Ge:Ga detectors, time constant: bias change, PACS-MA-TR-30</td>
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1.2.6 - D. Test Description

1.2.6 - D.1. Introduction

The goal of this test is to measure the dark current for each pixel. It also serves as reference for straylight assessment for different FPU environments (PACS test cryostat, Herschel cryostat for IMT/IST tests). Additionally, a scan of the detector temperature of the blue array should allow the determination of the band gaps of each pixel.

The specification for the dark signal is that the number of dark electrons per second should be less than $5 \times 10^4 \, e^-/s$ (see RD-8).

1.2.6 - D.2. Test Overview

The FM-ILT dark current measurements were carried out on 20 March 2007 during the FM ILT phase 2. The measurements were performed by staring at the switched-off calibration source ($T = 4.685 \, K$) by applying a constant chopper position of -21350. The grating position was constant at 50000 which corresponds to a wavelength of 219.3 $\mu m$ for the red array and 109.7 $\mu m$ (second order) for the blue array using the presently valid calibration file. The smallest capacitance of 0.14 pF (effective) was used for both arrays. Data acquisition was done in buffer transmission mode, that means raw ramps for each pixel were recorded for 10 s intervals followed by transmission breaks of 3 minutes. To avoid saturation of the ramps at higher blue detector temperature different reset intervals depending on the temperature were chosen: ramps with 2 s (512 samples) for the nominal temperature range, 1 s (256 samples) at a temperature of 3.2 K and 1/4 s (64 samples), at the highest temperature of 3.5 K. The bias voltage was set to 69 mV for the red array and 168 mV for the blue array.

The voltage range of the 16 bit ADC was assumed to be 6.26 V. The red detector temperature was rising from 1.821 to 1.834 K. For the blue detector 5 different temperatures were set to study the dependence of the dark current on the detector temperature: 2.079, 2.5, 2.888, 3.187 and 3.492 K. The signals (slopes of the ramps) were calculated by a linear fit to the raw ramps. The first 2 samples of red array ramps were discarded, because they are known to deviate (initial hook) (see Fig. 1.75).

1.2.6 - E. Results

1.2.6 - E.1. Red Array

In Fig. 1.76 the median of all dark current signals are shown for all pixels. The 4 known dead pixels and 2 known low response pixels can be discerned clearly. The signals of the nominal pixels range between 80000 and 300000 $e^-/s$, that is a factor of 2 to 5 above the specifications! The mean value without open and resistor channel and known bad pixels is $137320 \pm 48289 \, e^-/s$. The resulting values are in perfect agreement with the results of the FM-ILT/IST measurement (see RD-9) and are in very good agreement with the values measured at module level (see RD-6). There, the values varied between 100000 and 300000 $e^-/s$ for a bias voltage of 70 mV.

Remarkable are columns 4, 9 and 19 which show significantly higher signals. These modules are at the edge of the field of view and are known to be affected by a poor alignment of the image slicer. This could be a hint that these modules pick up (stray) light from other directions than from the cold calibration source.

From the visual inspection of Fig. 1.76 there is the impression that column 10 is brighter than the average. This might be due to cross-talk from the high signal column 9. This impression is confirmed by the results of the module level tests described in RD-6. At module level column 9 (corresponding to module FM162) and column 10 (corresponding to module FM189) had both a rather moderate and similar dark signal of about 150000 $e^-/s$ (at 70 mV bias), while column 11 (corresponding to module FM196) had a high dark current. During FM-ILT the central pixels of column 10 have a signal of about 190000 $e^-/s$ which is 27 % higher than at module level,
while column 11 shows a significantly lower signal level than at module level. This difference from the module level test results indicates that column 10 is affected by cross-talk from the adjacent high signal module 9. The bad resistor pixel in column 6 (FM168) seems to have an impact on the detector pixels. Due to its very low signal it affects the corresponding module by less cross-talk than the neighboring high signal resistor pixels do with their corresponding modules. This seems to be the reason for the comparatively lower signals of this module.

Like at FM-ILT/IST the dark current of the modules on the right hand side (supply group 1) is on average slightly lower than that of the modules of supply group 2 (left hand side) as can be recognized in Fig. 1.78.

1.2.6 - E.2. Blue Array

The blue array has a very low dark current, the ramps cover only a very small dynamic range and therefore look noisy (see Fig. 1.75). The dark values span a range from 2400 to 11000 $e^-/s$ and therefore clearly fulfill the requirements. The mean value without open and resistor channel and known bad pixels is $3512 \pm 1822 e^-/s$. Overall, the resulting values agree well with the measured ones of the module level tests (see RD-7). But the values are a factor of about 2 higher than measured during FM-ILT/IST (see RD-9).

There is a strong cross-talk from the dummy/resistor channel to the spectral pixel visible which is gradually decreasing from row 16 to 11 (see Figs. 1.76 and 1.78). This cross-talk leads to a general elevation of the dark signal level in these rows. This cross-talk is much stronger than observed at FM-ILT/IST; it is caused by a much higher checkout voltage applied to the dummy resistors (30 mV with respect to 0.3 mV at FM-ILT/IST). But there might be an influence of the dummy channel over the whole array: The dummy ramps are saturated and the resulting sharp bend in the ramps is visible over all science pixels and even for the open channel (see Fig. 1.77). Additionally, the dark current in the first few rows is between 2400 and 3600 $e^-/s$ which is still much higher than observed at the FM-ILT/IST. But it cannot be excluded that a different grating position used at FM-ILT/IST (500000 which resulted in a wavelength for the blue array of 89.8 $\mu$m with respect to 109.7 $\mu$m here) and therefore a different background radiation level could be the reason for the differences in the dark current values. The alternating bright/dark pattern of columns that appears between columns 11 to 20 is less clear than for the FM-ILT/-IST. Additionally, all open channels seem to be influenced (cross-talk) by their corresponding modules. They show higher signals for modules with an overall higher dark signal. That means that we have correlated noise on the channels, which the subtraction of the open channel ramps from all signal ramps should remove. Like at FM-ILT/IST the dark current of the modules on the right hand side (supply group 3) is on average slightly higher than for modules of supply group 2 (see also Fig. 1.78).
Figure 1.75: Examples of raw ramps for red and blue pixel [10, 10] with a linear fit superimposed, left panels: red pixel with increasing reset interval length from top to bottom, right panels: blue pixel with increasing reset interval length from top to bottom, the blue detector temperature of bottom panel was 2.09 K
Figure 1.76: Dark current signals converted to $e^{-}/s$ of red (top panel) and blue array (bottom panel)
Figure 1.77: Ramps of the blue module 10 from the dummy (17, top left) to the open channel (0, bottom right)
Figure 1.78: Top panel: median dark current spectrum of red array, bottom panel: median dark current spectrum of blue array. The supply groups are distinguished. The error bars reflect the dispersion of pixel values.
1.2.6 - E.3. Band Gap Determination

As can be seen in Fig. 1.79 the dark current of the blue array starts to depend on the detector temperature above 2.9 K with the following relation:

\[ I_{\text{dark}} \sim e^{-\frac{E_{\text{gap}}}{kT}} \] (1.1)

where \( E_{\text{gap}} \) is the band gap energy. Only the currents at the two highest temperatures were used to determine the band gap of the blue pixels, the result is depicted in Fig. 1.80. Most of the pixels have band gaps around 10 meV, the dispersion is very low. There are few pixels, especially in module 0, that deviate down to about 8 meV, these pixels also show a higher NEP than the average (see RD-10). This might indicate a somewhat higher stress on these pixels leading to a smaller band gap. Some modules showed lower band gaps down to 7 meV due to higher stress at module level tests, these seem to have disappeared. For the other modules there is very good agreement.

![Graph of dark current vs detector temperature](image)

Figure 1.79: Dependence of the mean dark current of the blue array on the detector temperature, the error bars indicate the pixel variations

The temperature of the red array was steadily rising during the long-term measurement saved in file FILT_Batch_Dark_RawDynRange_20070320_01.tm (see Fig. 1.81) and the average dark current of the red array seemed to depend on the temperature (see Fig. 1.82), although not significant. This effect, if significant at all, could also been caused by the shorter reset intervals of the integration ramps at the higher detector temperatures (see Fig. 1.81). The responsivity rises with shorter resets due to debiasing effects when applying long integration times as already stated in RD-6.
Figure 1.80: Band gap energies of the blue array

Figure 1.81: Temperature curve of the red array during the measurements
Figure 1.82: Dependence of the mean dark current of the red array on the detector temperature, the error bars indicate the pixel variations.
1.2.6 - F. Conclusions

- The tests were carried out successfully and meaningful dark signals for both arrays and band gap energies for the blue array could be derived using the applied set-up.

- The red array shows an excess dark signal above the specifications. The enhanced dark signal of some border modules might be affected by stray light due to remaining misalignment of some image slicer elements.

- The dark current of the blue array is much better than the specifications and in good agreement with the results of module level tests. There is a factor of about 2 with regard to the results of FM-ILT/IST.

- There is cross-talk from the resistor pixels which depends on the level of the applied check-out voltage. Applying a zero checkout voltage should be taken into account, if the resistor signals are not used for data analysis.

- There is a slight dependence of the dark current on the supply groups.

- Overall, there is good agreement with the results of the FM-ILT/IST and the module level tests.

1.2.6 - G. IA scripts used / remarks on PCSS

CAP_1.2.6.py

1.2.6 - H. Lessons learned for IMT/IST/PV

- The alignment should be improved and the expected reduction of the dark signal of some borderer modules be checked.

- The reason for the excess dark signal of the red array should be investigated in more detail, e.g. it should be tried to measure the dark current over a large range of the detector temperature to check if it was some kind of straylight or really a strong dependence of the dark signal on detector temperature.

- It should be considered to set the check-out voltage to zero in order to minimize the cross-talk from the resistor pixels on low level detector signals.

- The reasons for the supply group differences should be investigated.
1.2 Spectrometer Full System

Req. 4.1.1; 4.1.2; 4.1.3 FM-ILT3 Spectrometer Spatial Calibration

4.1.1; 4.1.2; 4.1.3 - A. History

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<td>A. Contursi</td>
<td>First issue</td>
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<td>0.2</td>
<td>November 12, 2007</td>
<td>A. Contursi</td>
<td>Added spec FOV in sky coordinates</td>
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4.1.1; 4.1.2; 4.1.3 - B. Summary

......

4.1.1; 4.1.2; 4.1.3 - C. Data Reference Sheet

Table 1.1: 27 x 27 raster file names, basic detector settings, On Board reduction, raster step and dwell time in each raster position

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Table 1.2: 9 x 9 raster file names, basic detector settings, On Board reduction, raster step and dwell time in each raster position

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4.1.1; 4.1.2; 4.1.3 - D. Test Description

We execute three 27×27 XY stage rasters, with a hole of 1.5 mm and an external Black Body at temperature equal to 1000 °C. The raster size has been conceived such that it slightly oversizes the spatial FOV size. All rasters start from module 24, proceeding from 24 to 20, from 15 to 19 etc. The step size in both the X and Y stage directions are 0.425 mm which corresponds to 1/4th of a spectral pixel, assuming that 1.7 mm is equal to one spectrometer pixel. Note that the X stage coordinate corresponds to -Y detector coordinates (assuming the origin of the detector coordinates in module 0) and the Y stage coordinate corresponds to the X detector coordinates, (see figure 1.83 this document and figure 12 of PACS-ME-DS-003 Issue 1.0 page 17) and to the direction of the chopper movements.

We have executed three 9×9 rasters, with a hole of 1.5 mm and an external Black Body of 1000 °C, raster step equal to 0.425 mm (i.e. 1/4th of spectrometer pixel). The rasters were all centered on module 12th in order to
fully sample the PSF in this module. In fact, in FMILT–2, we executed a 5×5 raster centered on module 12, and this was not sufficient to get the full PSF.

The three 27×27 rasters were executed at the same grating position 709000 (corresponding to 76.9 and 153.8 μm) varying the chopper positions to -11580, 650, and 12444 (command units) which correspond to the -Large, (Optical) zero, and +Large chopper throws offered in HSPOT, which correspond to -3, 0 and +3 arcmin in the sky. These sets of data are meant to investigate the spatial distortion introduced by the chopper movements and the orientation of the detector with respect to the chopper movement direction.

The three 9×9 rasters, were executed at grating positions 927000, 461000 and 132000 all with the chopper in the Optical zero position. These data sets are meant to investigate the distortion induced by different grating position and to study the relative orientation of the chopper movement direction, the detector and the grating.

Table 3 summarizes all measurements. All data sets together allow us to study the PSF in each module, and in each spectral pixel, and the distortion induced by the optics and/or by chopper and grating movements.

Figure 1.83: Conversion between the XYstage coordinates direction and the XY detector array direction. Also the chopper movement direction is indicated.

4.1.1; 4.1.2; 4.1.3 - E. Analysis
After standard decompression, wavelength calibration (SPG module:waveCalc.py using FMILT–1 wavelength calibration from H.F.), we resample the XY stage coordinates informations, which are sampled every 2 seconds and delivered in the normal HK, to the Frames granularity (SPG module convXyStage2Pointing.py, after correction for the time problems found by D.L.). In this way, we can average together the Frames taken at the same raster positions.

The background subtraction is a tricky issue. In FMILT–3 we have used a better method than in FMILT–2 (see reports on Spectral Spatial Calibration of FMILT–2 analysis). In fact, we realized that the old background subtraction, done fitting a polynomial on the whole pixel’s history, was not good enough because it included also the part of the data where the pixel sees the source. This led to significant residuals which showed up as quite strong structures in the background. In this new version we have performed the same fit but excluding for every spectral pixel of each module, the time range where the pixels see the source. This is quite laborious because currently it is not possible to perform a fit only on ranges of data, asking the fit to ignore some part of the data. So, this has been done manually, excluding for each module (but the same for all spectral pixels of that module) that part of data containing the source and substituting these data with a straight line. Then a polynomial fit on these data has been done. The improvement is quite impressive especially for the BLUE (higher S/N than the RED channel) as one can see from figure 1.84.

Long but efficient, this method really gives a flat background centered on 0. Then, for every spectral pixel, and every module, we produce a 27×27 image, where each pixel corresponds to an XY Stage raster coordinate. In the 27×27 raster, the size is sufficiently big to ensure each module has a full well sampled PSF. The file FILT_20070613_27x27_chop_pL_01.tm is truncated because of a telemetry drop problem happened during the test execution. There was no time to repeat this raster and it covers most of the FOV anyway.

In the 9×9 raster, we cannot subtract the background as explained above, simply because these measurements are too short to ensure a good fit. We executed these “mini-raster” including an off position at the beginning of the recorded file, that we subtract then to the data.

Further analysis depends on the goals of the investigation and will be reported along with the different results.

4.1.1; 4.1.2; 4.1.3 - F. Results

4.1.1; 4.1.2; 4.1.3 - F.1. PACS spectrometer PSFs in each spatial module

We first produce the 27x27 raster for each module averaging all science spectral pixels. Then we did the same for the open and dummy channels only, which should not show any signal.
Figure 1.84: Example of the two methods used for the background subtraction. Method 1 (top panel), performs polynomial fit on the whole data, method 2 (bottom panel) performs polynomial fit only on that part of the data which do not show the source.

Results are shown in figures from 1.85 to 1.90. Figures 1.85 (BLUE) and 1.86 (RED) show the 5×5 FOV where each module shows the PSF obtained averaging all science spectral pixels. Data are for the same grating position (i.e. 709000 command units equal to 76.9 and 153.8 µm), and chopper position going from -Large to +Large from left to right in the figures.

Figure 1.87 shows the comparison for the BLUE channel of FMILT–1, FMILT–2 anf FMILT–3, at chopper position zero. From these figures we can notice the following results:

- The right column of the FOV, is not as week as it was in FMILT–2. We have basically recovered the entire spatial FOV.
- The bright spot which was visible on the left side of module 4 in FMILT–1 and FMILT–2, is gone completely.
- Every module of the RED channel shows a faint signal in the position of the PSF of module 11, which indicates cross talks.
Figures 1.88 (BLUE) and 1.89 (RED) show the 5x5 FOV obtained for the DUMMY channel only. We see that the RED channel shows a source in all modules at all chopper positions. This PSF is always in the same position and corresponds to the position of the PSF in module 11. This indicates strong cross talk from this module to the dummy channel. In the data of FMILT–2 only cross talk in the supply group 2 were detected, although this might be due to a poorer S/N with respect to the data taken in FMILT–3. We checked that this is not due to saturation effects. All data sets have signals well below 8 V/sec.

Some hints of crosstalk from module 11 is also visible in the blue, but it is much less strong than in the RED channel.

Figures 1.90 (BLUE) and 1.91 (RED) show the 5x5 FOV obtained for the OPEN channel only. Crosstalks presumably from module 11 are visible in supply group 4 (BLUE) as negative crosstalk at chopper position -Large. Some hints of crosstalks are also visible in the OPEN BLUE channel in all modules at chopper position 0. The crosstalks are very strong in supply group 2 of the OPEN RED channel at all chopper positions.

Figure 1.85: 5x5 spatial FOV of the PSF in the BLUE obtained averaging all spectral pixels, at grating position equal to 709000 command units, and chopper positions equal to -11580, +650, and +12444 command units. The raster corresponding to chopper position +Large has not been executed completely (see text for details).
Figure 1.86: 5x5 spatial FOV of the PSF in the RED obtained averaging all spectral pixels, at grating position equal to 709000 command units, and chopper positions equal to -11580, +650, and +12444 command units. The raster corresponding to chopper position +Large has not been executed completely (see text for details)
Figure 1.87: BLUE PSF in each module, obtained averaged all spectral pixels, at chopper position 0, obtained in FMILT–1 (left), FMILT–2 (center) and FMILT–3 (right).
Figure 1.88: 5x5 spatial FOV of the PSF in the BLUE for the DUMMY channel, at grating position equal to 709000 command units, and chopper positions equal to -11580, +650, and +12444 command units.
Figure 1.89: 5x5 spatial FOV of the PSF in the RED for the DUMMY channel, at grating position equal to 709000 command units, and chopper positions equal to -11580, +650, and +12444 command units.
Figure 1.90: 5x5 spatial FOV of the PSF in the BLUE for the OPEN channel, at grating position equal to 709000 command units, and chopper positions equal to -11580, +650, and +12444 command units.
Figure 1.91: 5x5 spatial FOV of the PSF in the RED for the OPEN channel, at grating position equal to 709000 command units, and chopper positions equal to -11580, +650, and +12444 command units.
4.1.1; 4.1.2; 4.1.3 - F.2. Comparison between the theoretical and the observed PSF

Figures 1.92 and 1.93 show the comparison between the theoretical PSFs at 76.9 and 153.8 μm, obtained convolving the PSF at these wavelengths with a hole of 1.5 mm, and the observed PSFs at the same wavelengths. We show the comparison for the BLUE and the RED channels, only for module 0, 12 and 24, although the results are similar for all others modules. These figures clearly show that the agreements between the theoretical and observed PSF is excellent and we can therefore conclude that the PSFs is as expected in all modules at the sampled wavelengths.

4.1.1; 4.1.2; 4.1.3 - F.3. Distortion

For each of the 27×27 raster, we fit the PSF obtained in each spatial pixel, either averaging all spectral pixels, or in each spectral channel, with a 2d Gaussian, obtaining the σ and the x, and y position on the array of the peaks. We then transform each peak position into XY stage coordinates. The results are shown in figure 1.94. It shows the XY stage coordinates of the PSF peak position for the RED and the BLUE overplotted, for each chopper position, and at grating commanded units equal to 709000. The crosses represent the commanded XY stage coordinates during the tests. We note that:

- the spatial FOV is rotated w.r.t. the XY stage. The angle of rotation is a function of the chopper which might indicate that the array is rotated also w.r.t. the chopper. This is illustrated in figure 1.95 where the rotation in degree of the RED and BLUE arrays has been calculated from the XY stage position of the last row (module from 20 to 24).
- the displacement of modules from 5 to 9, is still there, as expected, since the mirror movements done before FMILT–3 test campaign begun, was not supposed to modify this aspect.
- no significant differences of the FOV fingerprint between the different chopper positions are noticeable.

Figure 1.95 shows the rotation of the FOV with respect to the XY stage coordinates, as function of the chopper position. We see that this rotation is significant and decreases as the chopper throw increases. The rotation goes from ~4.5° to 2.5° degrees going from -Large to +Large chopper throw. Also important the rotation seems to be the same for the RED and the BLUE array. In this figure we have also included the same measurements done for FMILT–2 data, where we had two more chopper positions (at ± Medium chopper throw). The overall agreement is good, but the dispersion of the data between the RED and BLUE points is much less in FMILT–3 than in FMILT–2. This is probably due to the higher S/N the data taken in FMILT–3 have w.r.t. the data taken in FMIL–2 and the better background subtraction we apply to the FMILT–3 data.
Figure 1.92: Cayan: observed monodimensional profiles of the PSFs obtained averaging all spectral pixels for module 0 (left), 12 (middle) and 24 (right), at grating commanded units equal to 709000, chopper position at Optical Zero, in the BLUE (up) and RED (bottom). Orange: theoretical PSF at the same (i.e. 76.9 \mu m) convolved for the 1.5 mm hole. The monodimensional profile have been obtained along the x array dimensions which corresponds to the Y stage direction.
Figure 1.93: Cayan: observed monodimensional profiles of the PSFs obtained averaging all spectral pixels for module 0 (left), 12 (middle) and 24 (right), at grating commanded units equal to 709000, chopper position at Optical Zero, in the BLUE (up) and RED (bottom). Orange: theoretical PSF at the same (i.e. 76.9 µm) convolved for the 1.5 mm hole. The monodimensional profile have been obtained along the y array dimensions which corresponds to the X stage direction.
Figures 1.96 and 1.97 show the fitted PSF peak XY coordinates for the BLUE and the RED respectively, obtained in FMILT–2 and FMILT–3. There is a displacement of about one half spectral pixels between the two. It is also noticeable in the RED channel (figure 1.97) that the last slice (from 20 to 24) position in X stage coordinate, is different from what obtained in FMILT–2. Currently its distance from the next slice (from 15 to 19) is much more similar to the distance the other slices have. This means that the RED channel is less distorted than what found in FMILT–2.

Figures 1.98 (BLUE) and 1.99 (RED) show the position of each PSFs peak for each spectral pixel. As found already in FMILT–2, these figures clearly indicate that there is a displacement of the PSF peak in the spectral domain both in the BLUE and in the RED channels. The displacement becomes more and more severe going from module 0 to module 24. The maximum displacement is of about 0.8–0.9 mm \textit{i.e.} one half of pixel, in both channels for module 24.
Figure 1.94: PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units.
Figure 1.95: Calculated rotation between the spatial FOV and the XY stage as function of chopper. Also shown are the rotation angles calculated in FMILT–2 for comparison.
Figure 1.96: FMILT-2 - FMILT-3 BLUE PSF peak position comparison, of each module on the XY stage coordinates (i.e. sky coordinates) for chopper positions at Optical zero, grating position equal to 709000 command units.
Figure 1.97: FMILT–2 - FMILT–3 RED PSF peak position comparison, of each module on the XY stage coordinates (i.e. sky coordinates) for chopper positions at Optical zero, grating position equal to 709000 command units.
Figure 1.98: BLUE PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units and for every spectral pixel.
Chop @ – Large  

Chop @ Opt. 0  

Chop @ + Large

Figure 1.99: RED PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units and for every spectral pixel.
4.1.1; 4.1.2; 4.1.3 - F.4. Spatial FOV in the sky as function of chopper position

Since we have calculated the position of each spatial module is in XY stage coordinates (i.e. the Y stage coordinate) at each chopper position, we can how this this varies as function of chopper position. Figures 1.100 and 1.101 show the fitted PSF position of each module on the XY stage coordinates, for all chopper position at once for BLUE and RED respectively.

Beside the rotation of the FOV w.r.t. the XY stage coordinates we have already analyzed, (figure 1.95) there is also a distortion which depends on the chopper positions. It does not seem to be linear. It can be fitted with a $2^{nd}$ degree polynomial, but with more chopper poistions, this distortion may come out to be more complicated that this.

Figures ?? and 1.103 show the comparison between FMILT–2 and FMILT–3, where it is clear the difference in the RED position of the row composed by modules from 20 to 24. This difference, between FMILT–2 and FMILT–3 becomes more significant going from chopper position -Large to +Large.

4.1.1; 4.1.2; 4.1.3 - F.5. mm to arcsec scale

Assuming that the chopper positions corresponding to ±Large, are exactly ±3 arcminutes in the sky, we can derive the scale corresponding to 1 arcsec in mm in the XY stage coordinates. We can do this for each module and for the scale derived from the position of the modules on the XY stage between the -Large and optical zero position and between +Large and optical zero position. The results are displayed in figures 1.104 and 1.105 for BLUE and RED channel respectively. The expected conversion is : 0.181 mm equal to 1 arcsec. We see that the derived scale for each modules is very very close to the expected values for all modules and for both RED and BLUE channels.

4.1.1; 4.1.2; 4.1.3 - F.6. Spectrometer FOV in sky coordinates

From PACS-ME-DS-003 page three, we learn that f=37154 mm. This correspnds to the following conversion factor:
1" = 0.18 mm

Using this conversion factor, we can therefor transform the XY stage PSF position peak in each module and per each chopper position, in sky coordinates. We can calculate the distance in arcsec of each pixel w.r.t. a reference pixel. As reference we choose the PSF peak of module 12 in the BLUE channel at chopper angle equal Optical Zero and grating position equal to 709000 command units.

The result is illustrated in figure 1.106 for the RED and BLUE channels. It is interesting to note, that the distance of module 12 in arcsec between chopper position ±Large, is 180.7 and 180.2 arcsec, in excellent agreement with what they should be (± 3').

4.1.1; 4.1.2; 4.1.3 - F.7. Grating and detector alignement

The 9×9 rasters were executed moving the source on a grid centered on module 12. The aim was to get a PSF sampled at 1/4$^\text{th}$ of a spectral pixel of module 12 at fixed chopper position but moving the grating. The data
were reduced and analyzed as the big rasters (see Section E).

We then fit the PSF peak position at each grating position on module 12 and transform these coordinates in XY stage coordinates, exactly as we did for the $27 \times 27$ raster for all modules. Figurew 1.107 and 1.108 show the derived peaks for each grating position, including the one obtained for module 12 in the $27 \times 27$ rasters, on the XY stage coordinates. We can see that the derived XY coordinates of the PSF peaks at various wavelengths agree very well, with a dispersion less than $1/4^{th}$ of the pixels. This means that the grating movements do not introduce spatial distortion in both channels. The PSF at 183.9 $\mu$m does not have enough S/N for the Gaussian 2D fit to converge. This is why its corresponding symbol is missing in figure 1.107.

4.1.1; 4.1.2; 4.1.3 - F.8. Conservation of the flux

In order to check whether each module receives some signals also from other modules or looses some signal when the source is in between the slices, we have created a sort of total map. We have first normalized the background subtracted PSFs in each module with their peak, in the $27 \times 27$ rasters. If there are no additional or lost of signals while the source is moving, the result should be an uniform wide region everywhere but at the edges where the source is out of the spatial FOV.

The results are shown in figures from 1.109 and 1.114. Each of these figure displays for one channel (BLUE or RED) and one chopper position, in the top panel with the full dynamical range, in the bottom panel, cutting the highest values in order to quantify better the contribution of the discontinuities, if presents, over the background. The big crosses in each figure represents the fitted peak positions of the PSFs. The small crosses represent the coordinates of the $27 \times 27$ raster executed.

From these figures we can see the overall shapes of the spectrometer FOV, with its characteristic of having the second slice displaced with respect to the others and the whole FOV being rotated with respect to the XY stage.

In general we can also see that the BLUE channel is more homogenous than the RED channel. The variation above the median, although difficult to determine with precision without a proper flat fielding, is around 20% in the BLUE (but varies around this value). The RED channel has a big and intense signal in a position which is close to module 11. This is due to the fact that it is not possible to remove the crosstalk from this module in the single $27 \times 27$ images for each module. Its contribution can be as high as a factor of 3 to 4. Its position however, does not corresponds exactly to the peak position of module 11, although it is displaced towards the bottom of just $1/4^{th}$ of a spectral pixel. It is difficult to assess with these data whether this displacement is real or not, and if real, what does it tell us.

4.1.1; 4.1.2; 4.1.3 - F.9. Raster Maps

In this section raster maps of the PSF are shown. These maps have been done just shifting each $27 \times 27$ raster image of each module on top of each other using the fitted PSF position. Then, each pixel is devided by an integer equal to the times it has been summed up in the reconstructed map.

This exercise should be done after a proper RSRF correction, which is not available at the time this report is written. This implies that, although the background subtraction works well, some structure still remains and they are well visible in the final maps.
The maps are shown in figures 1.115 and 1.116 for the BLUE and the RED channels respectively and for the chopper position equal to the Optical 0.
Figure 1.100: BLUE PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units.
Figure 1.101: RED PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units.
Figure 1.102: BLUE PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units for FMILT–2 (crosses) and FMILT–3 (solid circles).
Figure 1.103: RED PSF peak position of each module on the XY stage coordinates (i.e. sky coordinates) for all chopper positions and grating position equal to 709000 command units for FMILT–2 (crosses) and FMILT–3 (solid circles).
Figure 1.104: Conversion between mm and arcsec for each module of the BLUE detector as seen from the data assuming that chopper at +Large, 0 and -Large corresponds to +3, 0 and -3 arcminutes in the sky.
Figure 1.105: Conversion between mm and arcsec for each module of the RED detector as seen from the data assuming that chopper at +Large, 0 and -Large corresponds to +3, 0 and -3 arcminutes in the sky.
Figure 1.106: Position in the sky of the Spectrometer FOV in the RED and BLUE channels, per each chopper position. The reference position (0,0) corresponds to module 12 in the BLUE channel at chopper equal to optical Zero.
Figure 1.107: 5×5 BLUE spatial FOV reconstructed from the 9×9 rasters around module 12 for grating position at 132000 (top-left), 461000 (top-right) and 927000 (bottom).
Figure 1.108: 5×5 RED spatial FOV reconstructed from the 9×9 rasters around module 12 for grating position at 132000 (top-left), 461000 (top-right) and 927000 (bottom).
Figure 1.109: Summ of the signal for the BLUE at chopper position + Large in its full dynamic range (top panel) and in its highest contour values.
Figure 1.110: Summ of the signal for the RED at chopper position + Large in its full dynamic range (top panel) and in its highest contour values.
Figure 1.111: Summ of the signal for the BLUE at chopper position + Large in its full dynamic range (top panel) and in its highest contour values.
Figure 1.112: Summ of the signal for the RED at chopper position + Large in its full dynamic range (top panel) and in its highest contour values.
Figure 1.113: Summ of the signal for the BLUE at chopper position - Large in its full dynamic range (top panel) and in its highest countour values.
Figure 1.114: Summ of the signal for the RED at chopper position - Large in its full dynamic range (top panel) and in its highest contour values.
We can clearly see that the resulting background has structures due to the fact that we have not flat fielded the images before combining them into the map. Nevertheless, in the BLUE channel two ghosts appear clearly: one on each side of the reconstructed PSF. In the RED channel the PSF is elongated on the left, and this is due to the crosstalk from module 11 present in each single image used to reconstruct the map.

A crude estimation of the most intense ghost reveals that it is negligible (0.1% level) with respect to point source photometry. But its contribution is presumably much more significant with respect to the more extended faint emission. With the current data it is not possible to quantify this contribution.

The estimated rotation angle between the direction defined by the ghosts and the PSF and the XY stage coordinates is $\sim 10^\circ$.

The distance of each ghost from the PSF is 2.97 and 2.77 spectral pixel for the left and right ghost respectively.
4.1.1; 4.1.2; 4.1.3 - F.10. Ghosts in the BLUE

The results shown in the previous section induced us to go back and check again the single PSFs images in each module.

The ghosts are clearly detected when one stretches the dynamical range of figures 3, as it is shown in figure 1.117. The path followed by the ghost is regular: ghosts in the first two columns of the spatial FOV are on the right of the PSF; ghosts of the last two columns are on the left of the PSFs. This could also mean that there are always two ghosts, one on each side of the PSFs, but only one at the time is visible since the amplitude of the raster is not sufficient to include both at the same time. Although not confirmed, this hypothesis could be strengthen by the fact that in the central column the ghost appears sometime on the right sometime on the left of the PSF. At the moment no explanation has been found for the origin of these ghosts. We do not know whether these originate in the external window, or inside PACS. It looks like their intensities vary as function of chopper position. Form figure ?? it looks like they are stronger when the chopper is at its Optical zero. But we believe this effect is more due to the goodness of the background subtraction, which is better for this chopper position than for the others, and therefore make the ghosts appear stronger. No firm conclusions on this point are possible without a proper flatfield.

4.1.1; 4.1.2; 4.1.3 - G. Conclusion

The main results of the FMILT–3 spectral spatial calibration campaign are the following:

- We have recovered the entire spatial FOV, both in the BLUE and RED channels.
- The observed PSFs are in excellent agreement with the theoretical PSF
- Strong crosstalks with module 11 are detected in the RED channel for science and dummy pixels in all modules; in the RED open channel only supply group 2 shows such strong crosstalks; in the BLUE channel crosstalks are much fainter but they probably exist as well.
- The spatial FOV is rotated w.r.t. the XY stage. The rotation angle is a function of the chopper position and it varies from 4.5° to 2.5° from -Large to +Large chopper throws.
- The position of each module on the sky varies for each spectral pixel. This variation increases smoothly from module 0 to module 24 where the spread on the spectral domain is maximum and corresponds to 1/2 of spectral pixel for both channels
- the mm/arcsec scale determined from the data, assuming that the chopper throws equal to ±Large and Optical zero exactly correspond to ±3 arcminutes and 0 arcminutes in the sky, is as expected, i.e. 0.181 mm = 1 arcsec, and the dispersion around this value for each module is very small
- The grating movements do not introduce significant spatial distortion
- Ghosts are visible in the BLUE channel, at all chopper position. Their origin is still unknown. Their contribution to the point source obtained at 76.9 µm with a Black Body of 1000 °C is negligible but it can be significant for fainter emission.

4.1.1; 4.1.2; 4.1.3 - G.1. Software tool used for the analysis

The standard decompression, application of some existing SPG modules, background subtraction and PSF reconstruction form the rasters, have been done within the DP Herschel software. Further analysis which
included robust 2D Gauss fitting, and writing and reading of tables, has been entirely done in IDL, because of lack of functionalities in DP and much more efficiency in IDL than in DP.

4.1.1; 4.1.2; 4.1.3 - G.2. Implication for IST and PV phase

The FMILT–3 test campaign has produced very nice data sets, suitable for addressing all main issues related to the spatial calibration of the spectrometer. The same test sequence is therefore suitable for being repeated in PV phase, with the inclusion of full raster at chopper throws equal to \( \pm \) Medium that we did not perform in FMILT–3 for lack of time, (priority I), and if possible full rasters at same chopper throw but different grating position to check whether all spatial pixels are not influenced by the grating movements as we could currently check only for module 12 (priority II).

In addition, these test campaigns should include tests time to investigate the origin of the BLUE ghosts. If they will be still present, meaning that they originate in PACS, we should map them carefully, and determine their contribution at different source flux levels and at different wavelengths. This could imply an additional calibration effort during operation, to map ghosts periodically in time at certain key wavelengths and nominal chopper throws, in order to be able to correct these out in the final images.
Figure 1.116: Reconstructed raster map in the RED, at 153.8 $\mu$m and chopper position equal to Optical Zero.
Figure 1.117: Same Figure as Figure 3, but with the dynamical range stretched such the ghosts are clearly visible.
Req. 4.3.2 Reproducibility and linearity of the spectrometer

4.3.2 - A. History

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4.3.2 - B. Summary

Description of measurements on reproducibility and linearity of the spectrometer and concerns requirements 4.3.2, 4.3.4, and 4.3.5.

4.3.2 - C. Data Reference Sheet

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Table 1.4: Overview of the measurements and OGSE temperatures used

4.3.2 - D. Test Description

A whole set of flux calibration measurements (requirements 4.3.1, 4.3.2, 4.3.4, 4.3.5) intended to determine the absolute flux calibration, the linearity and reproducibility of the spectrometer, are performed in the same way. These are staring measurements on the internal calibrator source CS1 and the OGSE blackbody. The OGSE blackbody temperature is modified in order to obtain different input flux levels (see Table 1.7). A large set of measurements was performed throughout FM_ILT2. In this report we discuss the block of measurements which were performed on March 19, 2007, in a sequential series. One flux calibration block with overhead time takes about 18 minutes.

Fig. 1.118 gives an overview of how the measurement is performed. Small grating scans are performed around a number of key wavelengths (see report on Absolute Flux calibration and Table 1.5). First a measurement on the internal source CS1 is performed, followed by the same grating scan on the OGSE blackbody. This is repeated for the second key wavelength. For the third key wavelength only a grating scan is performed on the OGSE. Figures 1.119 and 1.121 show how the signal varies during the measurement for the two detectors.

For the whole set of measurements input fluxes were calculated to get a range of input fluxes as can be expected during flight.
Table 1.5: Key wavelengths

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<td>A</td>
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Table 1.6: Flux densities at the selected key wavelengths for different OGSE temperatures (as derived with PCSS program PacsOGSE).

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4.3.2 - E. Results

In total 60 flux calibration measurements were performed as described above (of which 59 during FM_ILT II and one in part III). In the results below, only the series of measurements on March 19 is discussed. In the preparations for these tests, input fluxes were predicted for different OGSE temperatures. In some cases other capacitance values had to be used to avoid saturations of the red detector. This was based on the predicted fluxes and the experience with the initial dynamic range measurements in the FM_ILT. Basically for the blue detector almost all measurements could be done with the lowest capacitance value (0.14 pF). However for the red a smaller dynamic range was observed and a higher capacitance was needed. However this has not worked out properly. In the commanding the input capacitance values were mixed so that the higher value was used for the blue and the lower one for the red, leading to saturations for the latter detector. As three different wavelengths are observed for each detector, this effects only part of the measurement as the higher capacitance value was often only needed in the higher responsivity part of the spectrum. For the measurements described here, both detectors were set at the lowest capacitance value (0.14 pF).

After derivation of the signal per module pixel we also subtract the dark current. For the blue detector where the dark current is below 100 ADU/sec, this is only a small fraction of the observed signal in the present tests. For the red however, with a dark current signal well above 1000 ADU/sec, it is important that this signal is subtracted from the observed signal. See also report on the “Absolute flux calibration of the spectrometer”.

4.3.2 - E.1. Blue detector

Fig. 1.119 gives an overview of how the signal typically varies for different pixels in the central modules of the blue detector. No saturations are detected during this measurement. Some spatial pixels are vignetted (see report on Flat Field) and clearly have lower signals. This largely disappears in the measurement on 18 June 2007 in FM_ILT3.

To compare the results of the nine measurements performed, an average is made of the signal per module pixel for a small part of the grating scan. Grating positions between 534500 and 535500 are included. For the measurement on the internal source we simply compare the measured signals obtained on the constant input flux. For the measurement on the OGSE, the signal is divided by the input flux as calculated with the PCSS
Figure 1.118: Overview of the chopper positions, filterwheel position and grating position (scaled to fit in one plot).

program PacsOGSE.py.

The result for the observations at 87.8 µm is shown in Fig. 1.120. The observations were the first ones after the night batch and started after a 45 minutes wait time until the OGSE black bodies had stabilized at the requested temperatures. Nevertheless we see a fast decreasing trend in responsivity both in the CS1 and OGSE measurement of about 3%. When correcting the OGSE measurement with the response determined on the CS1, we obtain a reproducibility better than .5%.

Also the response does not vary for different input fluxes in the range observed here (1130 - 1760 Jy).

4.3.2 - E.2. Red detector

In Figures 1.121 and 1.122 we see 2 examples of how the signal varies throughout one measurement block for different pixels in the central modules of the red detector. Saturations happen each time for the 142 µm scan and in the second case nearly so in the 176 µm scan which is used in the analysis here.

To compare the results of the nine measurements performed, an average is made of the signal per module pixel for a small part of the grating scan. Grating positions between 534500 and 535500 are included. Fig. 1.123 shows the evolution of the response as determined from the measurements on the CS1. Here we see a slightly increasing response, with a total increase of 1.4% over the whole time range of the series, i.e. 2.7 hours. There are also 2 small dips in this trend. These occur after the observations on the higher OGSE temperature settings.

In Fig. 1.124 the measurements on the OGSE at 35.4 K show a small scatter of .25%. The measurements on the higher OGSE temperatures show a higher responsivity, up to 2.5% for the 39.1 K case. It is unclear what is causing this. Clearly the dark current has relatively high value (∼ 1700 ADU/sec) and the uncertainty in
the determination of it (see report absolute flux calibration) will have a larger impact on the determination of the response. Nevertheless, it is unlikely that this uncertainty would be sufficient to explain the difference in responsivity observed. The higher responsivity at 39.1 K is even more surprising as here we are clearly close to the saturation level, at least for some pixels.

4.3.2 - F. Conclusions

Linearity and reproducibility were investigated on a set of measurements performed on March 19 2007. The blue detector showed a very linear behaviour after an increase of input flux by 60% (starting from approximately the estimated background flux level). A small trend in the response in the subsequent observations could well be corrected for with the measurements on the internal source, after which only a scatter smaller than .5% remained.

The red detector showed a smaller change in response than the blue and the scatter was about .25% for the repeated measurements on the 35.4 K OGSE BB. However we find somewhat different (up to 2.5% higher) responsivity for the higher temperature OGSE BB.

4.3.2 - G. IA scripts used / remarks on PCSS
Figure 1.120: The response for the subsequent measurements as obtained from the internal source and OGSE measurements (normalised to the third measurement). There is a decreasing trend with a 3% higher responsivity at the first measurement. This trend would however disappear when correcting the OGSE measurement with the response measured on the CS1. The observations with higher input fluxes follow the trend and do not show a deviation in responsivity.

Own scripts were used and PacsOGSE.

4.3.2 - H. Lessons learned for IMT/IST/PV
Figure 1.121: The evolution of the signal for different module pixels of the blue detector throughout one measurement block. Most pixels are saturated in the grating scan around 142 µm on the OGSE (time approx. between 525 and 750 secs.).
Figure 1.122: The evolution of the signal for different module pixels of the red detector throughout one measurement block. Most pixels are saturated around 142µm on the OGSE (time approx. between 525 and 750 secs.).
Figure 1.123: The response for the subsequent measurements as obtained from the internal source measurements (normalised to the first measurement). There is an increasing trend with a 1.5% higher responsivity at the last measurement. The third and seventh observation show a small decrease. This happens after the higher input flux measurements on the OGSE.
Figure 1.124: The response for the subsequent measurements as obtained from the OGSE source measurements
(normalised to the third measurement and divided by the relative response measured on the internal source).
The OGSE 37.3 and 39.1 K measurements show higher responses.
4.3.3 - A. History

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<td>J. Blommaert</td>
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4.3.3 - B. Summary

A description is given of the determination of the responsivity values of the spectrometer as derived at key wavelengths.

4.3.3 - C. Data Reference Sheet

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Table 1.7: overview of measurements.

4.3.3 - D. Test Description

For the absolute flux calibration of the spectrometer we determine the responsivity at the so called key wavelengths. These were chosen in parts of the Relative Spectral Response Function which do not show strong spectral features. In orbit we will establish the flux calibration by measuring stellar calibrators at the key wavelengths and compare these with stellar models.

The responsivity values are determined from the same set of measurements as the ones used for linearity and reproducibility. See the report on requirement 4.3.1 for a detailed description. The OGSE temperature was set at 35.4K. The PCSS program PacsOGSE.py was used to determine the flux entering the instrument (see Table 1.8).

The measurements described here are “staring” measurements, i.e. a small grating scan is performed without movement of the chopper. Subsequently CS1 and then the OGSE blackbody is observed. An alternative measurement in which a chopped measurement on both internal sources is performed and for which the OGSE chopperwheel was used to simulate a chopped measurement between the two OGSE blackbodies. This measurement is not included in this report.

As we determine the responsivity in a staring measurement we need to subtract the dark current. Especially for the red detector this is important as the dark current is quite high in comparison with the measured signal on the internal sources and the OGSE BB (see also dark current report, requirement 1.2.6).

A dedicated dark current measurement was made which was planned to be executed in the same manner as the responsivity observation. Unfortunately because of a telecommand drop, midway the measurement, no further changes in grating and chopper occurred, so that in the second half the instrument was staring at the ‘cold’ CS1 in a fixed grating position. See figures 1.125 and 1.126.
4.3.3 - E. Results

4.3.3 - E.1. Dark current

Fig. 1.127 shows the temperatures of the two OGSE black bodies which are around 5.06 K and still slowly decreasing. No measurable input flux is expected even at 176 μm (expected flux observed per pixel is below 10 mJy or below .5 ADU/sec). Largest fraction of the time however the instrument sees CS1 which is also switched of and cold.

4.3.3 - E.1.1. Dark for the blue detector

Fig. 1.128 shows the variation of the signals for a set of pixels. The next figure zooms in and shows a slight increasing signal as function of time. However the trend is small and we average over the whole measurement to derive a “dark current” for the whole detector. Also there are no variations to be seen as function of changing chopper position, nor of changing signal as function of grating position.

We derive a “dark image” by averaging the whole measurement for each pixel (as is shown in Fig. 1.130). We find the following values: MEDIAN(whole image) = 79 ADU/sec (STTDEV(whole image) = 38 ADU/sec. This dark image is used to subtract from the image obtained in the responsivity measurement. There is a clear difference between the two supply groups:

Supply group 4: MEDIAN = 94 ADU/sec
Supply group 3: MEDIAN = 51 ADU/sec

4.3.3 - E.1.2. Dark for the red detector
Figure 1.126: Overview of the chopper positions, filterwheel position and grating position for the dedicated dark current measurement. Halve way, the grating and chopper positions remained constant.

Fig. 1.131 shows the variation of the dark signal for a set of pixels. Contrary to the dark measurement of the blue detector we see a difference between the measurement on the CS1 and the OGSE BB, with a lower signal on the OGSE BB. Nevertheless we believe that the largest fraction of the signal is caused by the dark current of the detector. A full grating scan on the cold OGSE BB was performed (FILT_SPEC_QuickFullSpectrum_coldBB1_20070323_01.tm). The resulting “spectra” are shown in Figures 1.132 and 1.133. In the scans we can see that only a small part (< 100 ADU/sec at peak response) of the signal is wavelength dependent and can be assumed to be caused by some sort of stray light (nature unknown at this stage). However the trend is small and we assume that we can use the measured signal as a measurement of the dark current, which we will need to subtract in the flux calibration measurements.

We derive a “dark image” by averaging over the part where the cold OGSE BB is observed for each pixel. The resulting dark image is shown in Fig. 1.134. We find the following values: MEDIAN(whole image) = 1730 ADU/sec (STTDEV(whole image) = 35 ADU/sec. This dark image is used to subtract from the responsivity measurement. There is a clear difference between the two supply groups:
Supply group 2: MEDIAN = 1935 ADU/sec
Supply group 1: MEDIAN = 1410 ADU/sec

4.3.3 - E.2. Responsivity

The responsivity values at different key wavelengths are determined by dividing the averaged signal observed at the grating position (±500) by the OGSE flux as determined with PacsOGSE.py. Table 2 gives the fluxes per pixel determined with this program and the responsivity values obtained.

4.3.3 - F. Conclusions
Figure 1.127: Temperature of the OGSE BBs

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Table 1.8: Flux densities (for a 34.5 K OGSE BB) and response values at the key wavelengths.

Responsivity values have been determined at key wavelengths. Together with the signals measured on the internal calibration sources, these will be included in the calibration file for absolute flux calibration of the spectra.

4.3.3 - G. IA scripts used / remarks on PCSS

PacsOGSE.py and own routines.

4.3.3 - H. Lessons learned for IMT/IST/PV

For the red detector, the contribution of the high dark current signal (and possible stray light issues) is the main uncertainty in the determination of the responsivity (see also report on linearity). With chopped measurements as planned in orbit, this will be less important.
Figure 1.128: Dark current evolution for the blue detector.

Figure 1.129: Zoomed in view of the dark current of the blue detector.
Figure 1.130: Dark current as derived for the whole blue detector.

Figure 1.131: Dark current evolution for the red detector.
Figure 1.132: Up and down full grating scan on the cold BB for Module 12.

Figure 1.133: Up and down full grating scan on the cold BB for Module 9.

Figure 1.134: Dark current as derived for the whole red detector.
Figure 1.135: The response map for the blue detector, obtained during FM_ILT2.

Figure 1.136: The response map for the blue detector, obtained during FM_ILT3.

Figure 1.137: The response map for the red detector, obtained during FM_ILT2.
4.3.8 - A. History

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4.3.8 - B. Summary

The Relative Spectral Response Function (RSRF) of the PACS spectrometer is the response of every pixel as a function of the wavelength of the infalling far-infrared radiation.

In principle, the (relative) spectral response function is the product of the (relative) spectral response functions of all components involved, namely, detector, grating, filters, PACS optics, telescope optics. By determining all these RSRFs the full system RSRF could be determined. However, measurements on component level are not available, and some effects are highly dependent on system characteristics (e.g. filter transmission depending on the angle of incidence), so the RSRF needs to be determined accurately on system level.

The RSRF was determined based on very detailed spectral scans over the entire wavelength range covered by the spectrometer in the different spectral orders of a cryogenic blackbody. The RSRF was measured at the optical zero chopper position, as well as at the large, medium and small chopper plateau positions used in the PACS AORs. For in-flight reference, the same detailed scans were performed on the two internal calibration sources.

In the course of the FM Instrument Level tests, the instrument was warmed up and stripped two times in order to perform re-alignment of important optical components to correct for severe misalignments in the instrument. We have performed a full RSRF characterisation at the 7 chopper plateaus and the two internal calibration sources after the first re-alignment, and a full characterisation at the optical zero and one of the internal calibration sources after the second re-alignment. Full scans at reduced spectral resolution were performed at the 7 chopper positions to translate the broad-band differences found in the full characterisation to the in-flight configuration.

4.3.8 - C. Data Reference Sheet

Table 1.9 lists all the RSRF-specific measurements and gives an overview of the sources observed, chopper position and integrating capacitance.

Table 1.10 shows the measurements that have been used to determine the detector signals under dark conditions.

Table 1.11 indicates the telemetry dump files where these measurements have been recorded.
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Table 1.9: Overview of the RSRF measurements during the ILT-2 and ILT-3 test campaigns. The CUS column refers to the CUS mode used: PACS_Spec_Rsrf_OBS (RSRF) or PACS_Spec_QuickFullSpectrum_OBS (Quick). Columns Cb and Cr refer to the integrating capacitance used in blue and red, respectively. Chop gives the chopper position, and CP indicates the standard AOR chopper plateau (Large, medium, small, ... ). Src refers to the source observed, and Tbb indicates the temperature (Kelvin) of the blackbody. Columns R1, B2A, B2B, B3A indicate if the respective band is covered in the measurement.

*aPinhole in front of 1000K external blackbody through cryostat window
bCryostat winddow background
cBB temperature not stable: T(BB1) +/- .1K
dGrating scan range limited from 400000 to 1063000.
Table 1.10: Measurements of cold blackbody and calibration sources switched off to determine straylight / dark current / amplifier offsets. Listed are the Observation Id (ObsId), date, CUS mode and blue and red integrating capacitance (Cb, Cr). The Quick full spectrum measurements cover the entire PACS spectral range, while the Wave_Cal measurements scan limited spectral segments.

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Table 1.11: Overview of the telemetry dump files corresponding to ObsIds in the observations overview in Table 1.9
4.3.8 - D. Test Description

A dedicated CUS mode PACS_Spec_Rsrf_OBS was defined to measure the RSRF over the entire PACS wavelength range. The RSRF measurements consist of an up/down spectral scan over the full grating range for the two filters in the blue chain. Grating step size is 133, which moves an unresolved spectral feature over less than 1/3rd of a spectral pixel. On every grating position in one scan, 5 integration ramps of .25 seconds are recorded before moving to the next position. This results in a measurement of 5.5 hours per filter, 11 hours for the full PACS range.

This measurement has been repeated several times, covering the following parameter space:

- Chopper dependence: measurements repeated at optical zero, and the chopper plateaus corresponding to the large, medium and small chopper throw in the spectrometer AORs.
- Leakage: to quantify spectral leakage, some measurements were repeated with different blackbody temperatures.
- Capacitance: The largest integrating capacitance for the red chain was chosen not to saturate in the high response parts on the relatively. Some measurements have been repeated with a smaller capacitance.

In order to translate the derived RSRFs to in-orbit, we have also acquired the same measurement on the internal calibration sources.

Details can be found in the overview of the measurements earlier in this section.

Due to time constraints during FM-ILT-3, the broadband shape at the different standard AOR chopping plateaus was verified using a coarse spectral scan. The CUS mode PACS_Spec_QuickFullSpectrum_OBS scans the full PACS spectral range in 1 hour in both filters.

4.3.8 - E. Data Processing

4.3.8 - E.1. Amplifier offset and detector dark current

The detectors provide a substantial signal under dark conditions. This can be seen in observation 536872335, when a full pacs spectrum was measured on the cold (5.9K) cryogenic blackbody source 1. In Fig 1.138 we plot the signal in the blue detector 9 of module 8. We see no difference between the data measured in filter A or B, nor between the data measured in the up and down scans.

In Fig 1.139 we plot the signal for red detector 9 in module 8. We see a strong change in the signal, especially during the first (up) scans after seeing the internal calibration source. We interpret the signal differences at different grating positions as due to the strong transient effects after the internal calibration source signal.

This measurement shows that (1) the signal under dark condition is very significant for the red detectors, and that (2) the signal is not changing more than a few percent at different grating positions. This signal is therefore an offset that is not caused by infrared flux passing through the optical chain. It can be due to detector dark
current, amplifier offsets and internal straylight. We need to subtract this offset from any detector signal before deriving a response calibration.

![Graph showing dark signals in red detector (9,8) as measured in observations 536872300, 536872305, and 536872301. The latter measurement was done with red capacitance 12. The comparison of the three dark signals shows that the reproducibility is not better than 50 ADU/0.25sec and that we can scale the dark signal with the nominal capacitance ratios.](image)

Figure 1.138: The signal of blue pixel (9,8) in the full scan of cold BB1.

In Fig 1.140 we show the dark signals in red detector (9,8) as measured in observations 536872300, 536872305 and 536872301. The latter measurement was done with red capacitance 12. We have scaled the dark signal with the nominal capacitance ratios. The comparison of the three dark signals shows that the reproducibility is not better than 50 ADU/0.25sec and that we can scale the dark signal with the nominal capacitance ratios.

We have constructed a dark signal map for all the detectors from observation 536872300 by taking a median of the signals in the entire measurement for every detector. The dark maps are shown in Fig 1.141 and Fig 1.142.

We scale the dark offset map with a factor depending on the capacitance used. The scale factor is based on the nominal capacitance ratios: 1 for capacitance 0 (140fF), 1.71 for capacitance 8 (240fF), 3.21 for capacitance 4 (450fF) and 8.21 for capacitance 12 (1150fF).
Figure 1.139: The signal of red pixel (9,8) in the full scan of cold BB1.
Figure 1.140: The signal of red pixel (9,8) in three different measurements of cold BB1.
Figure 1.141: The dark signal map of the blue array. The scale runs from -100 ADU/.25sec (black) to 0 ADU/.25sec (white).
Figure 1.142: The dark signal map of the red array. The scale runs from -1200 ADU/.25sec (black) to 0 ADU/.25sec (white).
4.3.8 - E.2. Processing of the RSRF measurements

After decompression the on-board fitted slopes and the corresponding grating positions were extracted per pixel. An example of the resulting data can be seen in Fig 1.143.

![Figure 1.143: The data for one pixel after extraction of the on-board fitted slopes](image)

A noise filter was run on the up- and downscan separately (bins of 133 steps in grating position, oversampling factor 2, rejection if more than 3 sigma away from the median). Subsequently, the remaining data of up and down scan were rebinned together to the same grid.

Using the littrow equation parameters derived in the wavelength calibration for FM-ILT, we calculated the average wavelength seen in every pixel based on the grating position.

From the (wavelength, signal) dataset, the pixel-specific dark offset was subtracted (see previous section), a correction factor was applied to compensate for the integration capacitance used (i.e. multiplied with a factor of 8.21 for the red RSRF measurements taken with integration capacitance 12) and this signal was divided by the blackbody flux density at this wavelength, calculated using the pacsOgseFlux module in the common toolbox of the PCSS. The resulting RSRF is hence in ADU/0.25sec Jy for the smallest integrating capacitance.

4.3.8 - F. Results
4.3.8 - F.1. Calculated RSRF

Fig 1.144 shows the relative spectral response function for all pacs spectral bands in pixel 9 of module 12. Fig 1.145 shows the blue bands in more detail, while Fig 1.146 shows the red spectral band. The wide feature at the long wavelength side of the red band is due to spectral leakage: the flux at second order wavelengths 90-110 leaks and produces the feature.

![Graph showing relative spectral response function](image)

**Figure 1.144:** The relative spectral response function for all pacs spectral bands in pixel 9 of module 12.

Fig 1.147 to Fig 1.153 show the comparison between the signal versus grating position as measured on the 42K blackbody at the optical zero and the positive large AOR chopper plateau in the different spectral bands, both globally and zoomed in. Fig 1.154 to Fig 1.158 show the division of these datasets.

From these figures we can conclude:

- The small scale structure of the RSRF reproduces to a level of 0.3% peak-to-peak between different chopper plateaus. We estimate that this is limited by the accuracy of the two RSRFs.
Figure 1.145: The relative spectral response function of the blue PACS spectral bands in pixel 9 of module 12.

- The global shape of the RSRF is different to a level of 2%. A broadband correction to the nominal optical zero RSRF needs to be applied on data taken at these chopper positions.

This behaviour of the chopper dependence was observed during ILT-2. After the re-alignment of the spectrometer optics before the ILT-3 campaign (with the actual flight alignment) the time to re-characterise the RSRF was limited. Therefore, the RSRF was measured in full resolution at the optical zero, and on the internal calibration source 1 for in-orbit reference. To characterise the global shape corrections at the AOR chopper plateaus, low resolution scans were performed on these chopper positions. This allows for a full pre-flight calibration of the RSRF at the standard chopper positions, valid for the flight configuration.
Figure 1.146: The relative spectral response function of the red PACS spectral bands in pixel 9 of module 12.
Figure 1.147: Comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in bands B2A and B3A.
Figure 1.148: Small scale comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band B3A.
Figure 1.149: Small scale comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band B2A.
Figure 1.150: Comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band B2B.
Figure 1.151: Small scale comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band B2B.
Figure 1.152: Comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band R1.
Figure 1.153: Small scale comparison of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band R1.
Figure 1.154: Division of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in bands B2A and B3A.
Figure 1.155: Division of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band B2B.
Figure 1.156: Detail of the division of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band B2B.
Figure 1.157: Division of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band R1.
Figure 1.158: Detail of the division of the 42K blackbody signal at optical zero and +large chopper angle in pixel 9 of module 12 in band R1.
4.3.8 - F.2. Work in progress

- From the measurements at colder blackbody temperatures, the spectral leakage in the long-wavelength end of the red band can be explicitly determined, hence a correction based on the observed flux densities in the parallel order 2 can be used to apply a correction on PACS spectra where this data is available.

- External measurements of the 1000K blackbody source are used to verify that there is no unresolved fringing, not visible in the extended source measurements. The same measurements are used to verify the spectral leakage correction described above.

- The global shape correction for different chopper positions needs to be approached, e.g. with a polynomial function or a spline. It needs to be verified if interpolation between these global shape differences can be used to correct for the RSRF shape between the (measured) AOR standard chopping plateaus.

4.3.8 - G. Conclusions / Lessons learned for IMT/IST/PV

The in-orbit strategy is to verify the validity of the RSRF measured at very high S/N during the Instrument Level tests. If necessary corrections will be applied to the ILT RSRF based on detailed spectral scans of celestial calibration sources.

During PV, the detailed RSRF scan on an internal calibration source shall be repeated. This gives a first indication on the validity / corrections necessary on the ILT RSRF. This measurement can be done while the telescope has not reached a stable temperature yet, since the measurement is entirely internal.

The RSRF is further validated via deep spectral scans on celestial calibration sources for which reliable reference SEDs are available. These can be done similar to the chop/nod range scan AOR at the highest spectral sampling, over the full grating position range. This is repeated on different calibration sources that are chosen not to be affected by the same biases or uncertainties in our knowledge of the spectral shape.

The chopper-dependent difference in shape can be validated by repeating a full SED spectrum of the same bright source (spectral shape not necessarily known very well, as long as it is not variable) at large, medium and small chopper angle in the following 6 combinations: (+S/-S, +M/-M, +L/-L, +L/0, +M/0, +S/0)

Throughout the routine phase, the RSRF is monitored through the observation of detailed, deep spectral scans and shallow full range spectral scans of a non variable, bright source.

For this purpose, bright sky calibration sources (≤10 Jy), with well determined (1%) spectral shapes, not necessarily absolute flux calibrated. Bright sources (100Jy), not variable, point-source.

4.3.8 - H. Implications for AOR design

We could benefit from a dark offset measurement inside the AORs. The detectors, especially the red detectors, give a significant signal under dark conditions. This signal does not depend on grating position, hence this is an offset that needs to be subtracted before gain correction (relative or absolute). These offsets can be taken from a dark map calibration table, derived from calibration measurements, but more accurate dark offset values could be determined inside the AOR, e.g. by keeping one internal calibration source cold and include a staring measurement on the cold source at a low response grating position.