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DOCUMENT

Release Note for the *Herschel* SPIRE Fourier-Transform Spectrometer Background Subtracted Spectra

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1 Abstract

SPIRE Fourier Transform Spectrometer sparse mode observations cover all types of sources: point-like, extended and semi-extended. The targets, as proposed by the observers, may be embedded in a foreground or background emission. The standard pipeline processed data products were carefully analysed and those that were considered centred on point sources embedded in a background were further processed, using the smoothed spectra of the off-axis detectors to remove the fore/background contamination from the central ones. In total, there are 310 sparse mode observations for which we applied the background subtraction. With some caveats these are considered higher quality science products than the default ones from the standard pipeline.

2 Introduction

The SPIRE instrument consists of a three band imaging photometer and an imaging Fourier Transform Spectrometer (FTS). The FTS uses two overlapping bands to cover 191-671 μm (447-1568 GHz), the Spectrometer Short Wavelength (SSW) band covers 191-318 μm and the Spectrometer Long Wavelength (SLW) covers 294-671 μm.

The FTS can be used to measure spectra with different spectral resolutions: High Resolution (HR), Low Resolution (LR), Medium Resolution (MR) and High and Low Resolution (H+LR). However, the Medium Resolution mode was never used for science observations during the mission and any calibration observations that were observed in Medium resolution are converted to Low resolution by the pipeline.

Spectra can be measured in a single pointing (using a set of detectors to sample the field of view of the instrument) or in larger spectral maps, which are made by moving the internal beam steering mirror (spectral maps) and/or the telescope (raster observations). For either of these, it is possible to choose sparse, intermediate, or full Nyquist spatial sampling.

Many of the observations with the Herschel SPIRE FTS are performed in sparse mode, where the target is placed in the co-aligned central detectors of the two FTS bolometer arrays. This is the most suitable observing mode for sources that are smaller than the FTS beam (FWHM 17”-42”). The surrounding detectors from both arrays also register spectra from the surrounding sky area. The Herschel Science Archive (HSA) provides high quality science products, but in cases when a point source is embedded on a foreground/background emission, removing the foreground/background emission using the off-axis detectors will result in spectra with much higher science quality than the original pipeline data. In some cases, especially for very faint targets, even though there may not be a significant emission in the off-axis detectors, the removal of the median “zero” signal could improve the spectral shape, because this zero signal is actually the residual telescope or instrument emission. The observations that would benefit from background subtraction have been identified and later processed and saved as Herschel Highly Processed Data Products (HPDPs).

Note that these HPDPs cannot be produced automatically by the pipeline as human decision is needed, based on a visual inspection using shorter wavelength maps (from PACS), knowledge of the source type (eg quasars, distant galaxies, pre-stellar cores, SN remnants, PNs), FTS spectra behaviour in the overlap region of the two

bands, etc. As this decision is also subjective, the users should consider carefully whether to use the background subtracted spectra, especially when they have better understanding and have additional information regarding the source properties and its environment.

As side products of the visual checks, other types of sources were classified under “extended”, “semi-extended”, sources with “pointing offset” and “problem” cases. This valuable info will be added to the Quality Control Report attached to each observation in the Herschel Science Archive. Those classified as “problem” will be further investigated by the SPIRE FTS team. If possible, they will be reprocessed by instrument experts, in order to try to improve the science data quality.

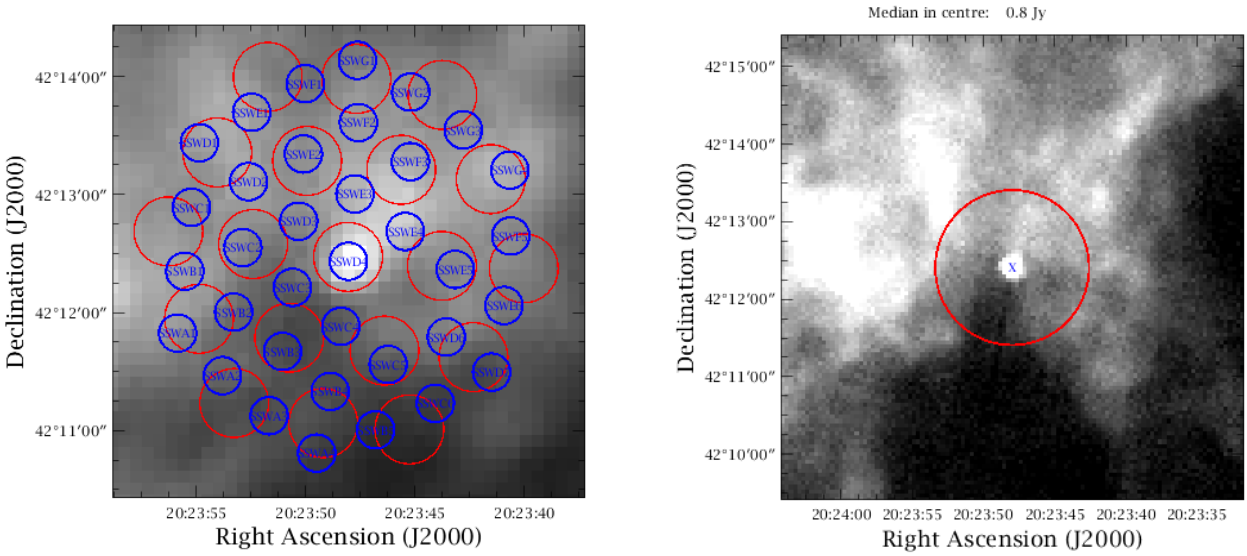


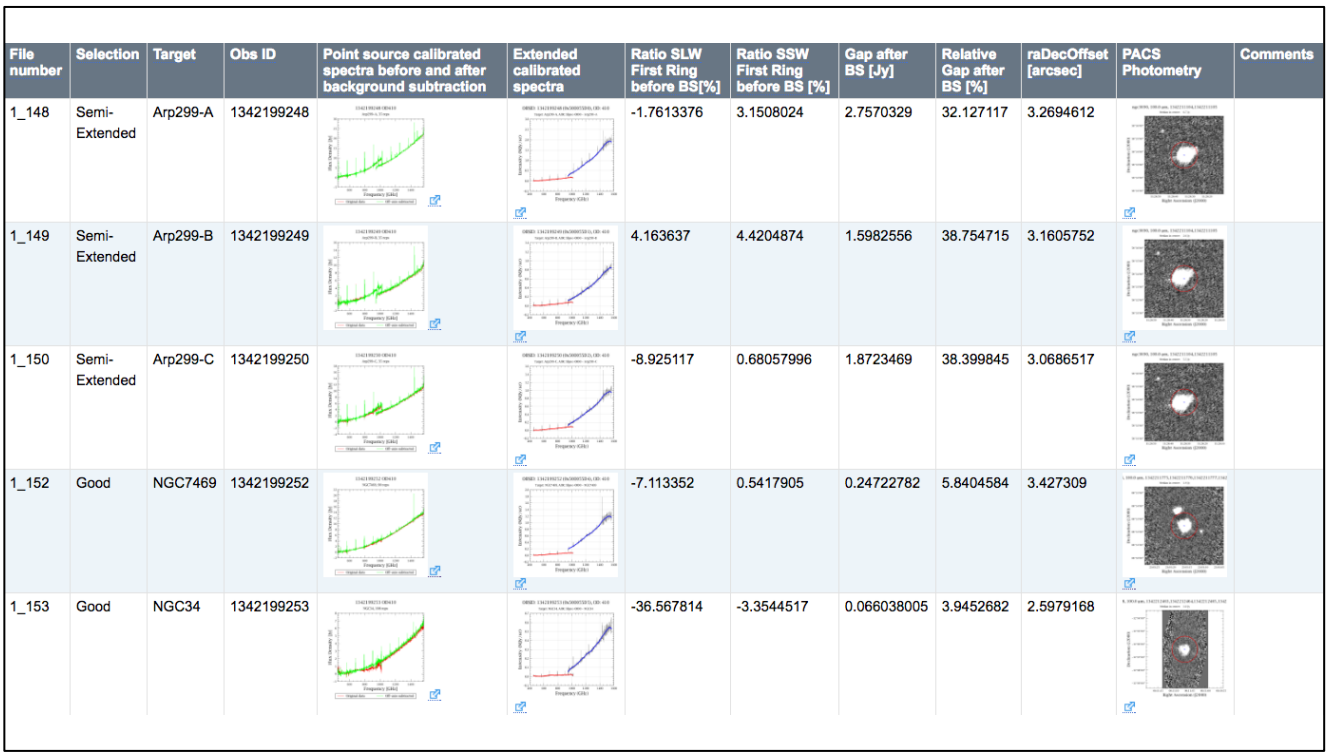
Figure 1. Left: footprint of the FTS bolometer arrays on the SPIRE 250 µm map. The target name, as provided by the observer, is V1515 Cyg-1 (or alternatively CygX NW-1). Right: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Clearly the central source is point-like and it is embedded in a region of extended emission. We use the first and the second ring of SSW detectors (small blue circles) and the first ring of SLW detectors (red circles) to obtain the smoothed median background spectra that are subtracted from the two central detectors.

3 Method

To begin with the identification of the point source targets that would benefit from background subtraction all sparse mode observations were processed using a general background subtraction script, available in the Herschel Interactive Processing Environment (HIPE), under SPIRE useful scripts.

We also used the extended calibrated spectra, in order to skip sources that may be fully extended or semi-extended. In this decision we also added PACS 70 µm maps, when available.

Different ratios were calculated and provided in the wiki table (as shown in Figure 2):



File number	Selection	Target	Obs ID	Point source calibrated spectra before and after background subtraction	Extended calibrated spectra	Ratio SLW First Ring before BS[%]	Ratio SSW First Ring before BS [%]	Gap after BS [Jy]	Relative Gap after BS [%]	raDecOffset [arcsec]	PACS Photometry	Comments
1_148	Semi-Extended	Arp299-A	1342199248			-1.7613376	3.1508024	2.7570329	32.127117	3.2694612		
1_149	Semi-Extended	Arp299-B	1342199249			4.163637	4.4204874	1.5982556	38.754715	3.1605752		
1_150	Semi-Extended	Arp299-C	1342199250			-8.925117	0.68057996	1.8723469	38.399845	3.0686517		
1_152	Good	NGC7469	1342199252			-7.113352	0.5417905	0.24722782	5.8404584	3.427309		
1_153	Good	NGC34	1342199253			-36.567814	-3.3544517	0.066038005	3.9452682	2.5979168		

Figure 2. Screenshot of a wiki page, giving an example of the type of information that was used in the process of identifying the candidates for background subtraction. Link to the wiki page

Here are some details regarding the information provided in the wiki table:

- *Point source calibrated spectra before and after background subtraction:* The images include the point source calibrated spectra before the performance of the background subtraction mentioned and after for the SLW and SSW detectors. The flux is measured in Jy.

- *Extended calibrated spectra:* The images show the spectra processed using the extended calibrated pipeline, which is valid for targets that are larger than the spectrometer beam. This is the spectra before the background subtraction and is measured in W/m^2/Hz/sr units.

- *Ratio SLW First Ring before BS [%]:* This parameter refers to the ratio of the flux of the first ring of SLW off-axis detectors to the flux of the central detector.
  It was obtained by calculating the ratios of the flux of every SLW off-axis detector to the flux of the central detector for each value of frequency. In order to eliminate the dependency on frequency, the median was taken for each SLW off-axis detector ratio array, resulting in a single value for every one of them. The final value resulted from taking the median from these last values.
  The off-axis detectors used are SLWB2, SLWB3, SLWC2, SLWC4, SLWD2 and SLWD3.

- *Ratio SSW First Ring before BS [%]:* This parameter refers to the ratio of the flux of the first ring of SSW off-axis detectors to the flux of the central detector.
  It was obtained by calculating the ratios of the flux of every SSW off-axis detector to the flux of the central detector for each value of frequency. In order to eliminate the dependency on frequency, the median was taken for each SSW off-axis detector ratio array, resulting in a single value for every one of them. The final value resulted from taking the median from these last values.
  The off-axis detectors used are SSWD3, SSWC3, SSWC4, SSWE4 and SSWE3. (SSWD5 is a dead bolometer)

- *Gap after BS [Jy]:* This value refers to the gap between the SLW and the SSW spectra of the central detector in the overlap region (944-1080 GHz) after the background subtraction has been done. It is the median of the difference between the flux of the SLW central detector and the flux of the SSW central detector for each frequency value.

- *Relative Gap after BS [%]:* This value refers to the ratio of the gap between the SLW and the SSW spectra of the central detector to the flux of the SLW central detector in the overlap region (944-1080 GHz) after the background subtraction has been done. It is calculated dividing the difference between the flux of the SLW central detector and the flux of the SSW central detector by the flux of the SLW central detector for each frequency value.

- *raDecOffset:* The offset between the commanded position and the actual reconstructed pointing, which includes any systematic BSM offset (bsmOffset), but not the APE. Included in the observation's Meta Data.

- *PACS map:* The maps used are the 'HPPUNIMAPB' data from Level 2.5 of the PACS photometer.
  In PACS photometer Level 2.5 data there are several maps, which are the combination of the scan—cross-scan pair (the most common observing mode of the PACS photometer, and in which the scan and cross-scan were two separate observations). The difference between the several combined maps provided is the mapping technique used to create them**. '**HPPUNIMAP[R|B]' maps were created by Unimap. Blue maps are used in both cases due to the better spatial resolution compared to the Red maps.

4 Classification of objects

The method used to correct the spectra of the observations depends on the target and how it is classified. The classification of the targets was necessary to identify the point source observations that would benefit from the background subtraction without removing emission from the actual source. There are targets that, although not being a point source, may present visually good results, when background subtraction is applied. This would lead to an erroneous interpretation of the science data provided, because some fraction of the flux that is subtracted may be from the source itself.

The following groups were used to classify the type of source and identify the way in which to proceed with the observations.

- "Good" – Cases with higher quality products after background subtraction.

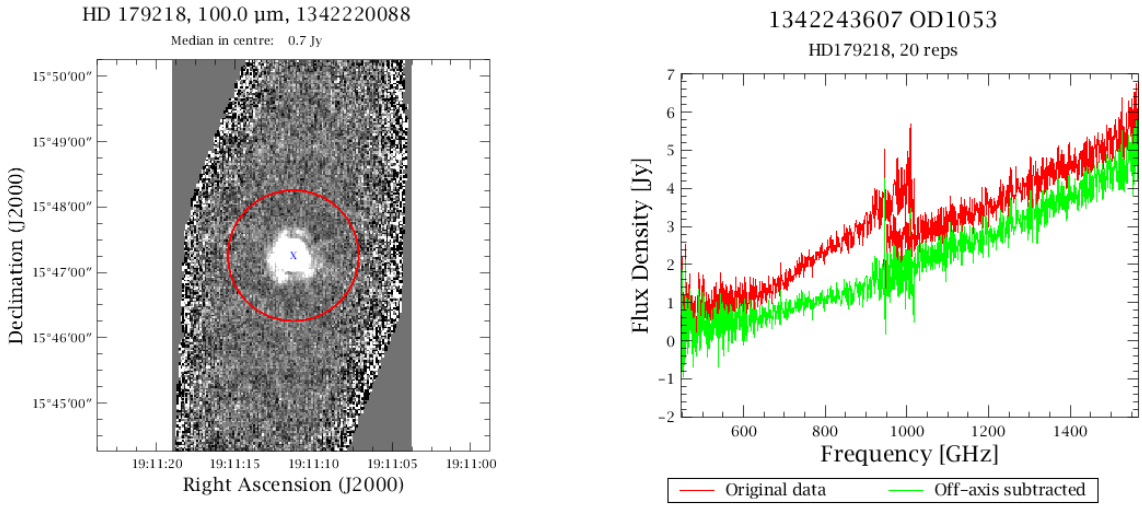


Figure 3. Example of an observation selected as a 'good' case. Left: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Right: SPIRE FTS spectra of the central detectors before and after the background subtraction.

- "Extended" – Uniformly extended emission over a region much larger than the spectrometer beam. Clearly an extended source. A note about the extended nature of the source is included in the Quality Report associated to every *Herschel* observation.

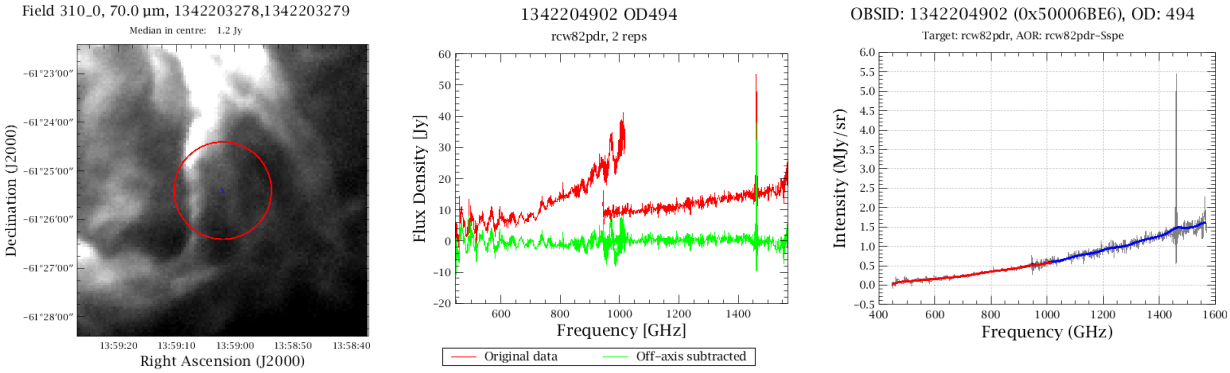


Figure 4. Example of an extended source. Left: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Central: SPIRE FTS spectra of the central detectors before and after the background subtraction with point source calibration. Left: SPIRE FTS spectra of the central detectors with extended source calibration.

- "Semi-extended" – Extended source with spatially dependent distribution. Potential semi-extended target. Correction is possible but it requires scientific assessment and additional information regarding the source. Quality Report INFO message.

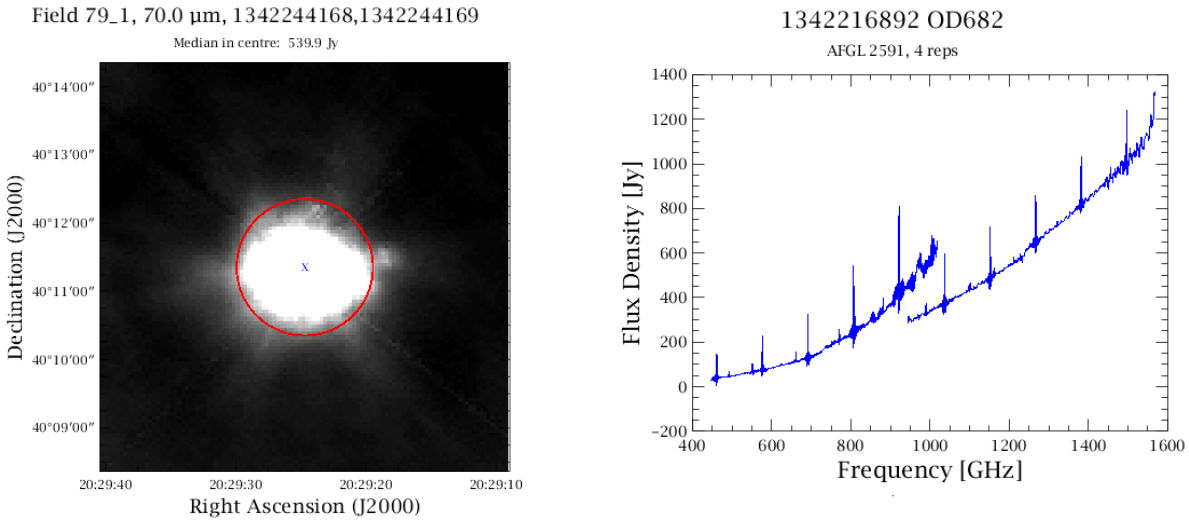


Figure 5. Example of a semi-extended target. Left: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Right: SPIRE FTS spectra of the central detectors with a point source calibration.

- "Skip" – Sources that present insignificant difference between original and background subtracted spectra. The spectra require no processing. This class also includes some special calibration targets as Neptune, Uranus, Saturn, Titan, Mars…

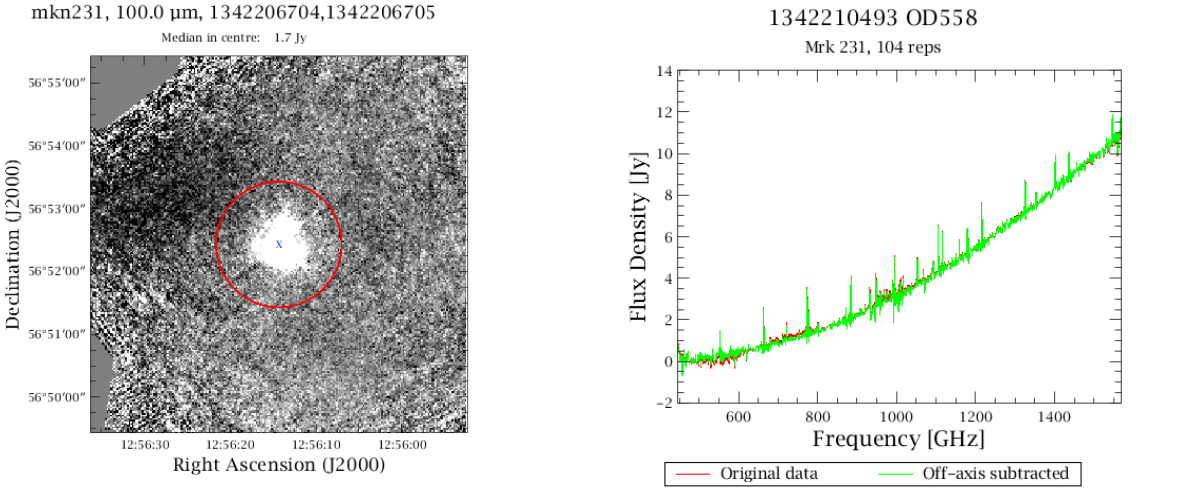


Figure 6. Example of a skipped target. Left: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Right: SPIRE FTS spectra of the central detectors before and after background subtraction. In the image it is clearly seen how there is almost no difference between the spectra before and after the background subtraction.

- "Pointing offset" – It includes sources which are clearly known to be a point source (eg a distant quasar) but the overlap region of SLW and SSW still presents a discontinuity. Nothing to be done at this stage. Can be corrected using the PointingOffsetetCorrectorTool available in HIPE v14. Quality Report INFO message.

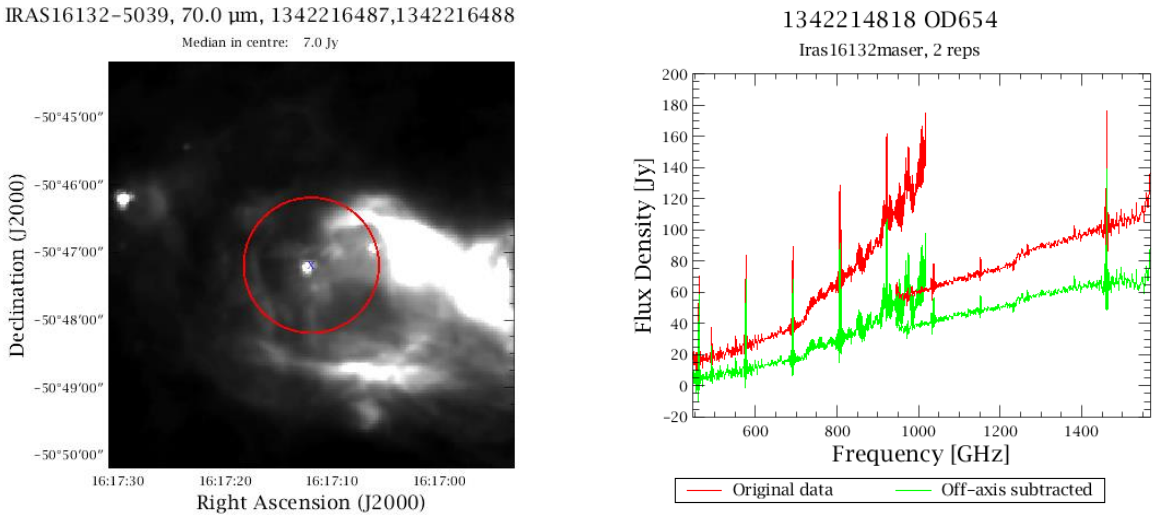


Figure 7. Example of a point source target with a possible pointing offset. Left: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Right: SPIRE FTS spectra of the central detectors before and after background subtraction. Although there is a visible improvement in the spectra, it is still not scientifically correct. The PointingOffsetCorrectorTool available in HIPE v14 should be used.

- "Problem" – problematic cases with strange spectral shape or unusual behaviour in the overlap, eg SSW above SLW (poor non-linearity correction). These sources need further analysis on a case by case basis by an instrument specialist. Quality Report INFO message.

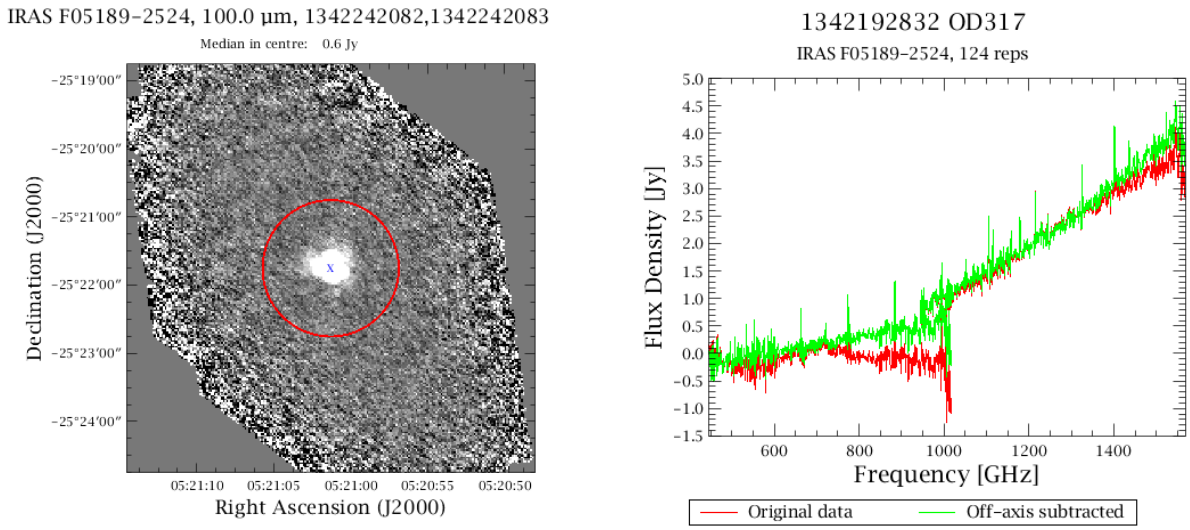


Figure 8. Left: outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 µm map. Left: SPIRE FTS spectra of the central detectors before and after background subtraction. This spectra exhibit this shape because of the poor non-linearity correction, usually when the instrument was very during an observations.

5 Background subtraction of the FTS spectra

In order to identify the observations that would benefit from background subtraction this method was applied in a standard manner to all sparse mode observation, regardless of the spectral resolution, i.e. both high and low resolution observations.

The 'Dark Sky' calibration observations are not included because they wouldn't benefit at all from this correction. The targets analysed in Hopwood et al. (2015) were also skipped, as they were already studied and corrected thoroughly in the mentioned article.

For the subtraction of the background emission two different arrays of detectors were used: the first ring of off-axis detectors of SLW (SLWB2, SLWB3, SLWC2, SLWC4, SLWD2 and SLWD3) for the subtraction on the SLW central detector emission and the second ring of off-axis detectors of SSW (SSWF3, SSWF2, SSWE2, SSWD2, SSWC2, SSWB2, SSWB3, SSWB4, SSWC5, SSWD6, SSWE5) for the subtraction on the SSW central detector emission.

First, the spectra of the selected off-axis detectors were smoothed using a Gaussian kernel function with a width of 21 GHz. The smoothed spectra were added to a list in order to calculate the median as a function of frequency. Then the median is subtracted from the original spectra of the central detectors. This is done separately for SLW and SSW.

The median estimation is usually robust against outliers, although it is not perfect. That is why, once the "good" observations have been identified with the simple median procedure, we perform an improved filtering of the outliers using a sigma-clipping method. This results in a better estimation of the background emission in the off-

axis detectors.

In the following image an example of a “good” observation spectra is shown, after applying the background subtraction using the 3sigma-clipping method mentioned above. The top figure includes the spectra before and after the background subtraction and the bottom figure shows the off-axis detectors that were included in the subtraction. It also incorporates the median spectra that were subtracted from the central detectors.

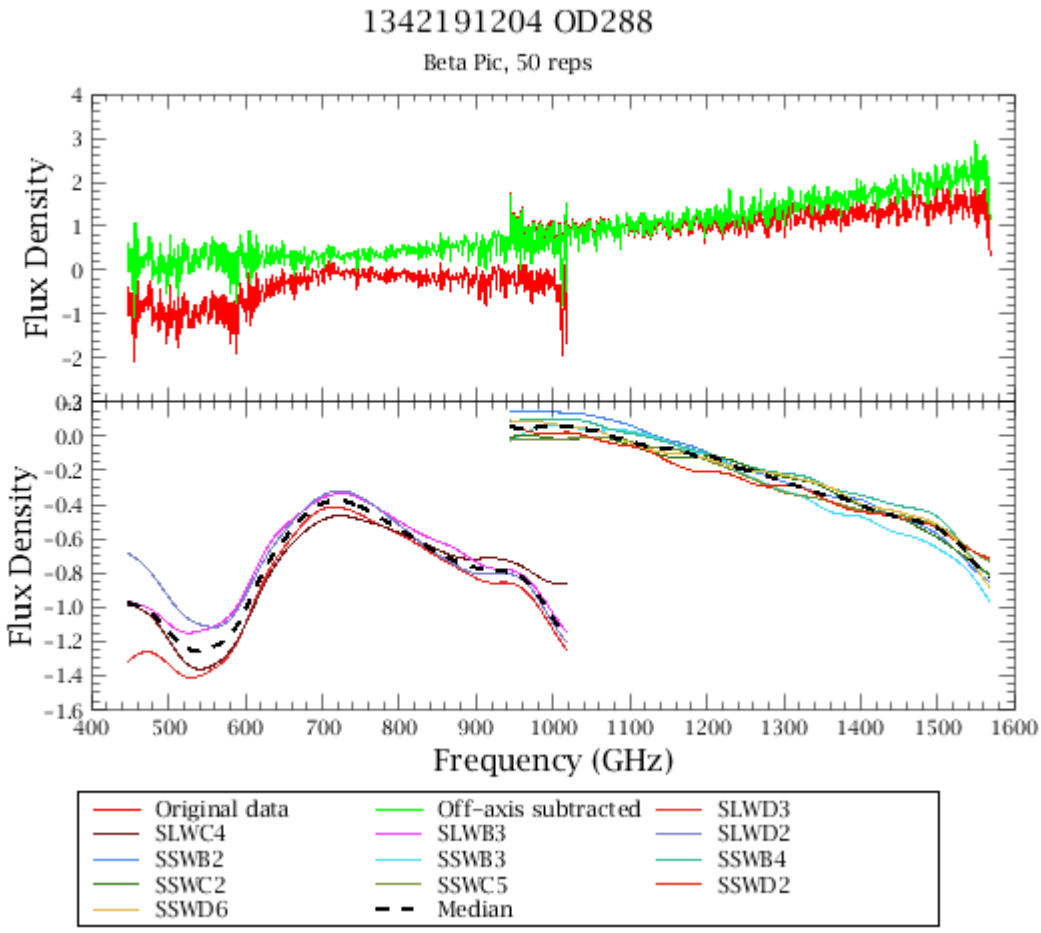


Figure 9. Example of a 3sigma-clipping results, showing the spectra of the central detectors before and after the background subtraction and the smoothed spectra of the off-axis detectors used to calculate the median that was finally subtracted. This kind of figure is used as a postcard for the provided background subtracted HPDPs.

5.1 Caveats

Here we summarise some caveats that need considerations before the user ”blindly” starts using the background subtracted spectra.

- The selection of targets for background subtraction is based on visual and semi-empirical evaluation of the spectra and PACS maps. As such, it may not be correct in some cases.

- There are a number of observations, like the one shown in Figure 10: looking at the PACS 70 μm map we see a clear point like source embedded in an extended emission. The subtraction of the background emission was performed, but it is possible that the point source, seen in PACS 70/100 μm image, may not have detectable emission in the SPIRE FTS bands. In those cases, the background-subtracted spectra may not be useful. Similar cases are listed below:

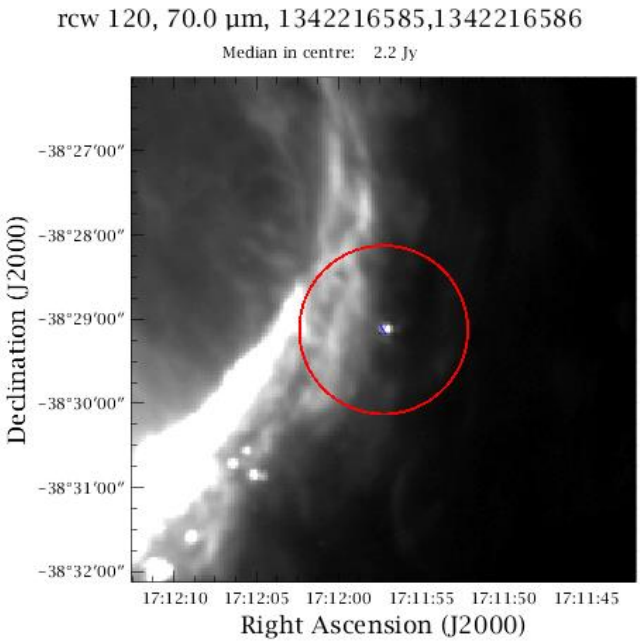


Figure 10. Outline of the full FTS unvignetted field of view (radius 1 arcmin) on the PACS 70 μm map for target with observation ID 1342214822.

File number (wiki page)	Observation ID
2_117	1342214822
2_118	1342214823
2_119	1342214824
2_120	1342214825
2_127	1342214839
2_128	1342214840
5_45	1342251286
5_47	1342251290
6_160	1342268308

6_161	1342268309
6_162	1342268311

5.2 Guidelines for semi-extended sources

Semi-extended sources are sources that are neither point-like (i.e. showing no discontinuity in the point-source calibrated spectra) nor fully extended (i.e. no discontinuity in the extended calibrated spectra). We do not provide background-subtracted spectra for such targets. Without knowing the source size we cannot select the off-axis detectors that will not include emission from the source itself.

If the user is familiar with the source brightness distribution then this information can be used to manually select the off-axis detectors. After this, the script in the Appendix (or the HIPE SPIRE Useful Script: Spectrometer Background Subtraction) can be used to perform the background subtraction with the selected detectors. Finally the Semi-Extended Correction Tool (SECT, Wu et al. 2013), which is provided as a task in HIPE, can be used to correct the background subtracted spectra for the source size.

6 Content of the HPDP

The background subtraction method was applied successfully on 310 FTS observations. A link to the wiki table, with the list of OBSIDs and the additional information, as in Figure 2, is provided in the Appendix.

6.1 Deliverable format and structure

The background-subtracted spectra are provided as Highly Processed Data Products (HPDP) and for each observation the HPDP contains the following files:

- Background subtracted FITS file per OBSID. The FITS filename is:
  <OBSID>_BackSubt_median3sigma_cen.fits
  where <OBSID> is the corresponding OBSID.
- The corresponding postcard, in PNG format, similar to Figure 9. The PNG filename is:
  <OBSID>_BackSubt_median3sigma.png
- This release note.

The structure of the FITS file is shown in the following table:

Name	Type	Notes
PRIMARY	PrimaryHD	Metadata for the OBSID
0000	ImageHDU	Not used
SLWC3	BinTableHDU	Background subtracted spectrum for the SLW central detector SLWC3
SSWD4	BinTableHDU	Background subtracted spectrum for the SSW central detector SSWD4
History	ImageHDU	Ignore
HistoryScript	BinTableHDU	Ignore

HistoryTask	BinTableHDU	Ignore
HistoryParameters	BinTableHDU	Ignore

Each of the two tables for the central detectors contain some relevant metadata and the following columns:

Column	Description
wave	The frequency in GHz
flux	The flux in Jy (point-source calibrated)
error	The error on the spectrum in Jy
mask	The mask column, currently FTS spectra have no masked data points, so ignore.
numScans	The number of scans for this spectrum

6.2 HPDP queries in the HSA

The background-subtracted spectra will be available under the HPDP menu in the Herschel Science Archive.

7 References

- Wu et al, 2013, A&A, 556, 116
- Hopwood et al, 2015, MNRAS, 449, 2274
- SPIRE Handbook, 2014, version 2.5

8 Appendix

8.1 The wiki pages

These are available in the following link.

The sections "NewPage#" are the breakdown into pages of the initial processing used in the source selection. The split in pages is only for convenience.

Once the selections have been made, the observations were included in the following wiki tables, under their category:

- Skip
- Good
- Extended Source
- Semi - Extended Source
- Pointing Offset
- Problem

The only targets that are provided as background-subtracted spectra in the HPDP are those in "Good" category.

8.2 Scripts

The script for the background subtraction, implementing the 3sigma-clipping strategy is available here.