QUICK-START GUIDE TO HERSCHEL–PACS
THE SPECTROMETER

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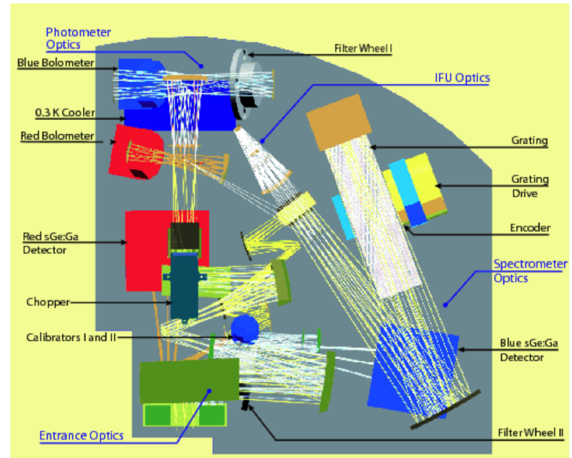
Contents

The PACS spectrometer

The PACS instrument. The Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al., 2010) consists of a three-band imaging photometer and an integral field spectrograph. This far-infrared instrument operated on board the *Herschel* Space Observatory (Pilbratt et al., 2010) between May 24th 2009 and April 30th 2013. A schematic of PACS, showing the light paths for the photometer and spectrometer sections, is shown on the right. The entrance portal to information about PACS can be found on the PACS overview page.
In this quick-start guide we deal with the PACS spectrometer.

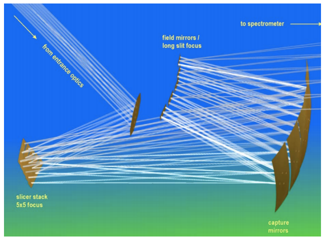


Some general characteristics of the PACS spectrometer are presented in the following table.

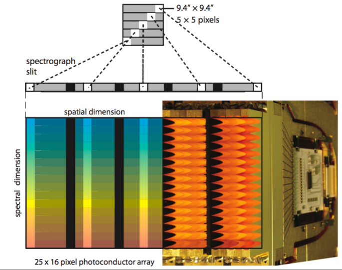
Band	B2A[a]	B3A[a]	B2B	R1[b]
Wavelength (μm)	55–72	55–70	70–95	103–190
R ($\lambda/\Delta\lambda$)	1700	4000	2250	1500
Instantaneous FoV	$47'' \times 47''$: 5×5 grid of $9.4''$ spaxels			
Beam FWHM ($''$)	~ 9	~ 9	~ 9	10–13

a: 51–55 μm is provided as HPDPs without flux calibration
b: 190–206 μm is provided as HPDPs with a special flux calibration

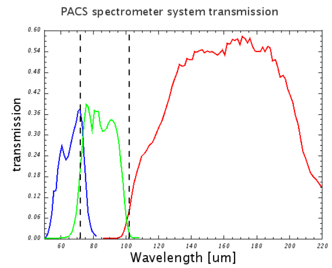
Image Slicer. The PACS integral field unit was an image slicer. The FoV was first sliced into five rectangular segments via mirrors, and the segments were arranged along a single length, as shown to the right. From there the light was directed, via the grating, on to the detector arrays, where each segment was further divided into five (as shown below). The PACS IFU is therefore a 5×5 spaxel grid covering $47'' \times 47''$.



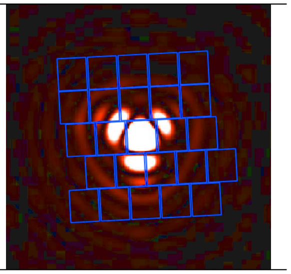
Ge:Ga detector arrays. The PACS detectors were Ge:Ga crystals arranged on a 25×18 grid, one each for the red and blue camera. On the right is a schematic showing the slicing of the FoV into five segments and the division of each segment again into five, spliced with an image of the detector array. The 25 columns of the detector captured the light from the entire FoV. The central 16 'spectral pixels' from each detector column gathered between them the entire spectral range requested; pixels 1 and 18 were not exposed to the sky.



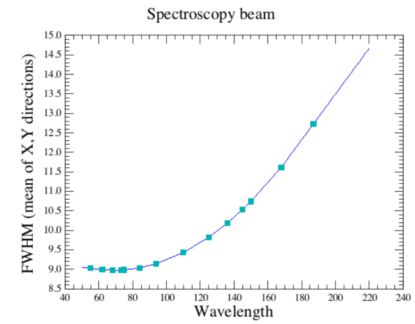
Spectrometer bands. The figure shows the overall transmission of three of the four bands in the three grating orders of the spectrometer. The vertical lines mark the edges between three of the spectral bands: B3A (blue), B2B (green) and R1 (red).



IFU sky footprint. Each of the 25 spaxels covers a $\sim 9.4''$ square patch of sky. However, the spaxels are not completely contiguous and the sky footprint of the PACS IFU is slightly irregular: the image is of the blue beam with the IFU footprint overplotted. It should be noted that the spaxel sizes are similar to the FWHM of the beam in the blue and only slightly larger in the red, meaning that the beam is spatially under-sampled in any single pointing.

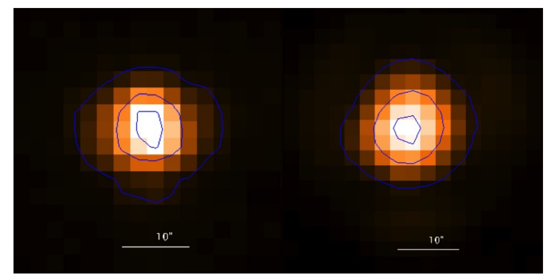


Spatial resolution and spectrometer beams



The plot to the right shows the Gaussian width of the measured beam, with the key wavelengths highlighted. The spectroscopy beam is the PSF as seen by the PACS IFU. For pointed and tiled observations, the beam is under-sampled, and this degrades the accuracy with which the morphology of observed sources can be reconstructed. Mapping observations were designed to result in a better spatial sampling, as the beam is then at least Nyquist sampled, allowing for a better reconstruction of the source morphology.

Details of the derivation and use of the beam as part of the PACS calibration are given in the PACS Handbook. The beams are the basis for flux aperture corrections related to the spatial distribution of the source (e.g. point-source and semi-extended source corrections), and of pointing correction tasks of one of the pipelines. The beam was mapped via rasters on Neptune at 14 wavelengths from 55 μm to 187 μm. A beam image is provided for each wavelength and for each of the 25 spaxels in HELL (level 2) ("PACS Spectrometer Beams ...."), together with explanatory notes. The beam image data are also provided in the calibration files 'PCalSpectrometer_BeamsPerSpaxel<BAND>_FM_v4.fits', but it is easier to use the maps provided in HELL (level 2). Beam data can also be downloaded from the Ancillary Data Products page: modelled beams and measured beams. Beam images for two wavelengths (62 [left] and 150 μm [right]) are shown to the right (scale bar is $10''$: slightly larger than the spaxel size). The spaxel size dominates the width of the beam up to 150 μm.



Spectral resolution and the wavelength grid

The spectral range and average resolution of the four bands (B2A, B3A, B2B, R1) are outlined in the table on p. 3. The spectral range varies with wavelength; plots of the spectral resolution vs. wavelength can be found in the PACS Data Reduction Guide (spec) (chp. 7.2). The spectral sampling of the data depended on the observing mode: ‘SED’ observations were sampled with a Nyquist density, ‘range scans’ could be taken with Nyquist or High density, and ‘line scans’ were taken with a High density. The sampling density affected the level of data redundancy (i.e. the number of unique data-points in each wavelength bin) – Nyquist density lead to a lower sensitivity depth of the spectra.

The 16 active spectral pixels of each spaxel covered a staggered wavelength range, i.e. the range for each pixel was slightly shifted with respect to that of its neighbour. The wavelength grid of each Level 2/2.5 cube is built by the pipeline from the wavelengths sampled during the observation by these 16 spectral pixels, creating a regularly-sampled grid that common to all spaxels of the cube. The area of lowest coverage, and hence lowest sensitivity, is situated at the edges of the spectral ranges (this being most noticeable in line and short range scans).

The science-level cubes produced by the PACS spectroscopy pipeline have a single wavelength grid for all spaxels in the cube, but note that the bin size of this grid scales with the resolution: the cubes have a *non-equidistant* wavelength grid, i.e. the sizes of the wavelength bins are not the same through the spectral range of any observation. This was done to allow the spectral *sampling* to remain the same throughout the entire spectral range covered by PACS. However, external software may find it difficult to read cubes with a non-equidistant spectral dimension, as the spectral grid is encoded in the FITS extensions ‘ImageIndex’ (a 1D array) and ‘wcs-tab’ (a look-up table for the spectral part of the WCS; a FITS standard which is however not yet widely used). Therefore, a set of *equidistant* cubes were created from one chosen Level 2 and/or 2.5 cube for each observation, and these are provided as Standalone browse products (SBPs: see p. 15). The bin size for the equidistant grid is chosen to be about 1/3 that of ‘its’ Level cube. The spectra of the non-equidistant and the equidistant cubes look the same, but users should remember that the wavelength bins for the SBP cubes are smaller than is justified by the spectral resolution.

Plots demonstrating how the spectrum changes with wavelength grid, and comparing the equidistant to the non-equidistant spectra, can be found in the PACS Data Reduction Guide (spec) (chp. 7.2 and 7.3).

Spectrometer observing modes (AOTs)

Observers could choose between line- and range-scan AOTs, and within each of these several other choices were required to set the observing mode: how to measure the background ('chop-nod' and 'un-chopped'), and the pointing mode ('pointed' or 'mapping'). Two additional sub-modes offered at the beginning of the mission ('wavelength switching' and 'pointed with dither') were discontinued after the PV phase. The AOT release notes can be found in HELL (level 2), and the observing modes are described in the PACS Handbook.

All AOTs performed spectroscopy with the blue and red camera simultaneously, with a choice of three bands in the blue and one band in the red. The prime range is that chosen by the observer, and the parallel is that from the other camera. The table below lists the spectral ranges observers could get in an observation: for a range selected from band 1, a parallel range was provided 'for free' in band 2, and vice versa. Within any one observation – but limited to the Line/SED/Range grouping – spectral ranges from all rows could be chosen (up to a limit of 10). For the SED mode, however, only one row could be chosen for a single observation, so it was necessary to request two linked observations to cover the entire SED.

AOT	Band 1	Wavelength (μm)	Band 2	Wavelength (μm)	Sampling
Line scan	B3A	51–73	R1	146–220	deep
	B2B	71–95	R1	140–210	deep
	R1	102–146	B2A	51–73	deep
SED	B3A	51–73	R1	140–219	Nyquist
	B2B	71–95	R1	140–219	Nyquist
	B2A	51–73	R1	103–146	Nyquist
Range scan	Any range within the SED limits could be chosen				Nyquist/deep

Note: although the spectral range of PACS offered originally was 51–220 μm, the actual ranges provided in the standard products provided via the HSA are 55–95 μm, 103–190 μm: the ranges 51–55 μm and 190–206 μm are offered as HPDPs (un-calibrated for the blue, with a special calibration for the red).

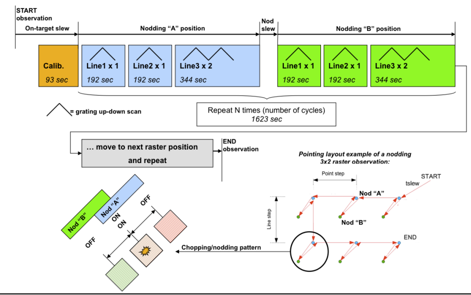
The AOT for each observation is given in the header data in the FITS files of any Level product. The keywords to look for are tabulated in the PACS Products Explained. The range of products provided for any observation varies with AOT, and the under/oversampled nature of the beam depends on the mapping mode. As an aide to archive users, a spreadsheet containing all the keyword values necessary to decode the AOT for all standard PACS spectroscopy observations can be found here.

AOT details

Wavelength coverage

The line-scan AOT covered a single unresolved line and its local continuum. Observers choose the band(s), set the central wavelength or chose from a set of lines, set the grating scan repetition factor, and they could specify the redshift and choose a bright-line mode. The range of highest sensitivity is approximately the central half of the spectrum for band R1 and the central third for the blue bands. The schematic to the right shows a typical pattern for a line-scan AOT.

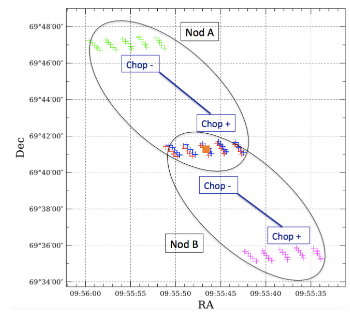
In the range-scan AOT one could specify any spectral range up to the entire band ('SED' mode). The inputs were the wavelengths, the repetition factor, and the spectral sampling density.



Background acquisition

The chop-nod was the standard mode for background subtraction: a high-frequency chopping (to move between the on-source and an off-source sky position, at each successive grating position) and a telescope nodding (performed after the entire spectral range had been gathered). Observers could choose between three chopper 'throws' and how often to repeat the entire nodding cycle. The figure to the right shows a typical sky pattern for a chop-nod observation.

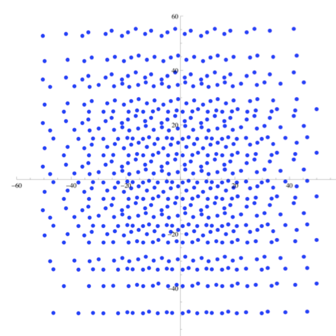
The un-chopped mode was offered for crowded fields, where no suitable off-position at the standard chopper throw angular separation could be found; instead, the telescope moved from the on-source pointing to a chosen off-source pointing after the entire spectral range had been visited. For line-scan AOTs, the off- and on-source data are included in the same observation, for range-scan AOTs the off-position was a separate observation.



Pointing modes

The pointed mode was aimed at compact sources. In this mode the beam is under-sampled, and the resulting 'native' cubes have the slightly uneven $47'' \times 47''$ sky footprint shown on p. 4.

The mapping mode was offered for large fields or to fully sample the beam. In the *oversampling* mode small offsets ($3''$[red], $4.5''$[blue]) over a defined raster pattern could be requested, resulting in an oversampling of the beam. In the *Nyquist*-sampling mode, larger offsets ($16'' \times 14.5''$[blue], $24'' \times 22''$[red]) over a defined raster pattern could be requested, resulting in Nyquist beam sampling. In the *tiling* mode, large offsets (anything $> 30''$) over any pattern could be requested; these data are also under-sampled. For un-chopped line-scans, the number of off-source visits was set in the AOT, but for un-chopped range scans the off-source position was always a separate observation. The image shows a pointing pattern for the 5×5 IFU with a 5×5 raster: the dots (collected centres of the spaxels) are within a few arcsec of each other.



Spectrometer flux calibration and uncertainties

The spectrometer flux calibration uses two schemes: for chop-nod observations the off-source data, which are measurements of the telescope emissivity, are used to derive the instantaneous detector response at every wavelength taken throughout an observation. These data are compared to the expected emissivity from an empirical model of the telescope that was fitted to full range spectra of Ceres and Pallas observed throughout the mission. For un-chopped observations, the detector response is determined from measurements on the internal calibration sources taken at the start of every observation. The absolute scale of the telescope model and the internal calibration sources were corrected to the flux-calibration measurements of the fiducial calibrators: late-type stars, planets, and asteroids. The models used were the same as for photometry. See the PACS Handbook for more detail.

PACS cubes have units of microns and Jy/pixel (where 'pixel' here means a spatial pixel, aka cube spaxel, whatever the actual size of the spaxel is). The fluxes of very extended sources (with a gradient of roughly no more than 20% over the FoV of the IFU footprint) are fully calibrated. For point, small, and extended+irregular/steep sources, extra flux corrections or considerations are necessary; see p. 18.

Type	Uncertainty	Comment
Absolute	RMS 12%, systematic 2%	Arises from the calibration source models, and errors imparted by pointing jitter, pointing offsets, and detector response drifts. The absolute calibration uncertainty applies independently to each band.
Repeatability	RMS 4%, chop-nod: peak2peak, 15% un-chopped: 20%	Reproducibility measurements of the same sources throughout the mission. **We recommend taking the peak2peak as the absolute calibration error: the distribution of errors is not Gaussian, and this value includes all of the most likely sources of error for any observation.**
In-band relative	chop-nod: 5% ($< 150\,\mu$m), 10% ($> 150\,\mu$m); un-chopped: 10%	The relative accuracy when comparing line fluxes within a spectral band, the accuracy on the continuum shape, and the detection limit for broad (few μm) features. Arises from differences in the RSRF/telescope background spectrum shape, transient effects, and pointing offsets. Determined from repeated measurements of Pallas throughout the mission.

Additional uncertainty information

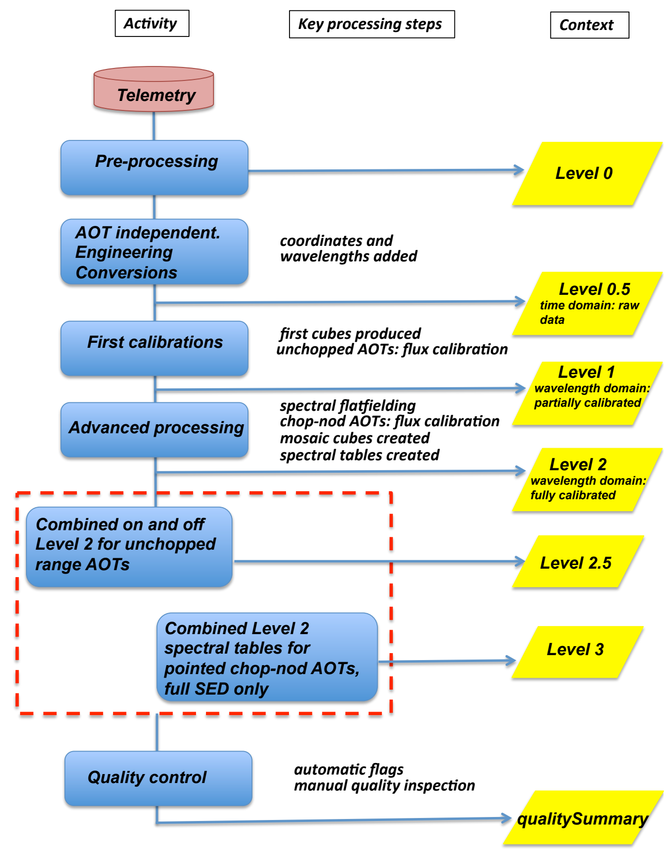
Continuum absolute level	**Un-chopped AOTs**: the absolute value of the continuum in this mode is not reliable; it was recommended to avoid this mode if observing continua of less than ~ 20 Jy. It has been since established that for **very bright sources the uncertainty can be up to $\pm$50–150 Jy, and for all other sources, $\pm$20 Jy** – this in **each spaxel** of each cube in an observation, where the value is for the 9.4$''$ sized re-binned cube spaxels. The continuum uncertainty is unique to each observation, as it arises from imperfect corrections for detector response drifts. **Chop-nod AOTs**: the uncertainty in the telescope continuum level for any observation means sources with < 5 Jy should be considered with caution.
$\lambda > 190\,\mu$m	The red end of the spectral range is affected by an order leak. A special RSRF was produced for this range and these data are provided as HPDPs. Comparison to overlapping SPIRE and HIFI emission lines from these HPDPs show that an additional factor of 1.3 will need to be applied to the HPDP line measurements. The continuum in this range is totally incorrect.
$\lambda < 55\,\mu$m	These blue wavelengths fall in low response and un-calibrated part of bands B2A and B3A. For observations that include ranges $\lambda < 55\,\mu$m, the relevant data are provided as un-calibrated HPDPs in the HSA. The continuum shape is unreliable in these data.
Errors in the cubes	All Level 2 and 2.5 cubes contain an 'error' or 'stddev' extension in the FITS files, calculated from the scatter in the datapoints that contribute to each wavelength bin (possible due to the high level of data redundancy). The units are Jy/pixel. This scatter is a good indication of the data noise.
Line measurements	If measuring the integrated flux of emission lines, the following guide can be used for combining the uncertainties: *For any single line*: line-fitting error plus the 15% absolute calibration uncertainty, with standard error propagation. *Ratio of lines within the same band*: standard line-fitting error propagation for the ratio and 10% in-band errors. *Comparing lines across bands*: standard line-fitting error propagation for the ratio and 15% absolute calibration uncertainty.

Spectrometer pipeline

The PACS spectroscopy SPG pipeline (the automatic pipeline) proceeds from Level 0 though to Level 2 for all AOTs. Levels 0 to 1 contain raw and partially calibrated data. Level 2 is first level with science-use products, and it contains a range of cubes and tables. Un-chopped range scans may have a Level 2.5, which are then the science-use products for those observations. Chop-nod pointed SED scans may have a Level 3, which is provided as a courtesy (containing a table concatenated from Level 2 tables).

A number of interactive pipeline scripts are provided in HIPE: the SPG scripts and interactive versions of the SPG script, and selection of additional pipeline scripts for different AOTs. The additional scripts include the 'Pointing Offset Correction' (POC) script, which can result in cleaner spectra than provided by the SPG for point sources that are off-centred; the 'Split On-Off' and the 'Calibration source and RSRF' scripts, which can both be used to check for contamination from spectral lines in the off-source pointings; and an additional transient correction script for un-chopped range scan observations. There are also a number of analysis scripts provided in HIPE that work from the SPG products, for example to: create fitted line maps from cubes; create cubes with different spaxel sizes; perform point-source corrections.

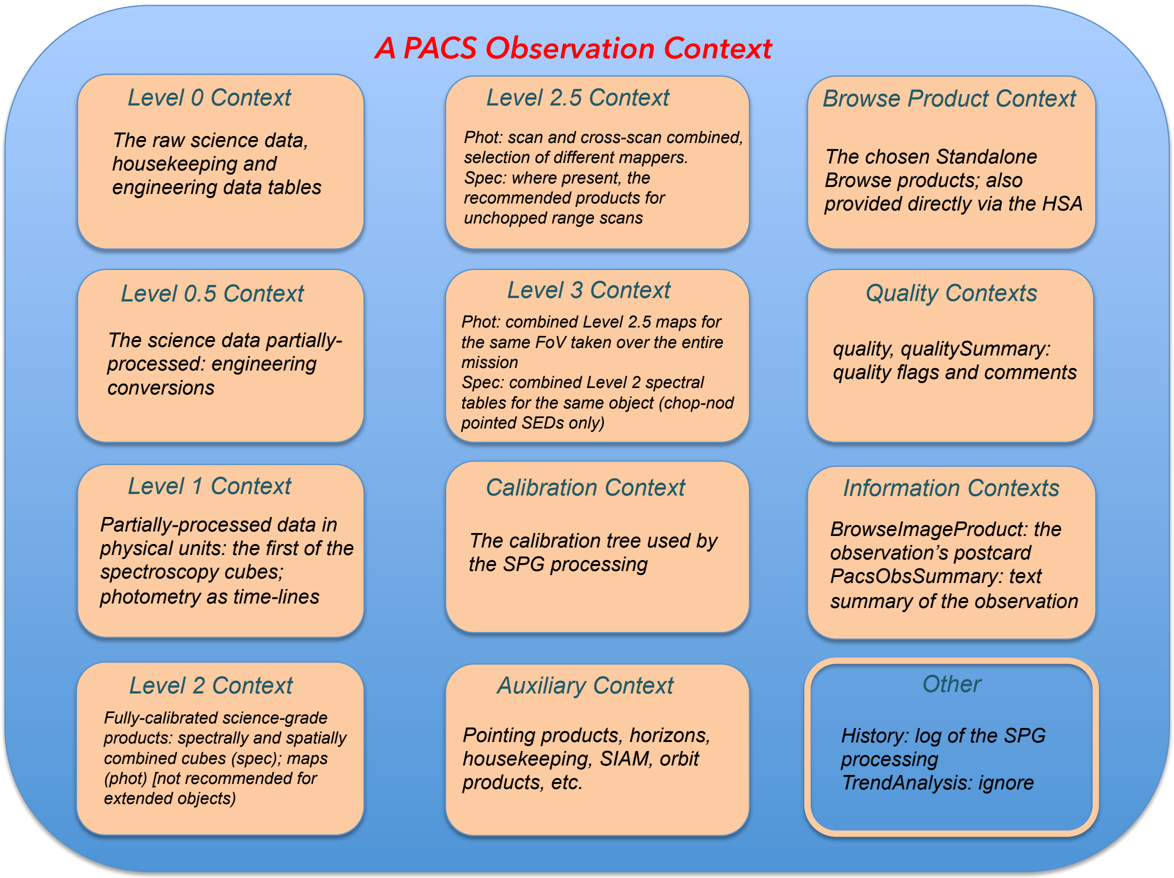
A step-by-step description of all scripts is presented in the PACS Data Reduction Guide (spec) and summarised in the PACS Handbook. Useful sections of the PDRG describe: what the cube-creating tasks do and the differences between the types of cubes (chp. 7); post-processing tasks for point to extended sources (chps 8 and 9); inspection tasks provided in HIPE for PACS cubes (chp. 10).



Data structure for PACS spectrometer: Observation context

In an *Observation context*, i.e. an observation downloaded from the HSA, the entirety of the data for any observation can be found: the raw data (Level 0), the reduced Levels (0.5 to 3), the calibration tree used to reduce the data by the SPG pipeline, auxiliary data, quality reports and – if viewing via HIPE – an observation summary. A schematic overview of the products held in an Observation context is given below. For more information see the PACS Handbook and the PACS Products Explained.

An Observation context downloaded from the HSA unpacks with a directory structure that reflects the pipeline levels and the product types, with FITS file names that reflect the product type and sequence.



High level description of the levels in the PACS spectroscopy Observation Context

All AOTs reach **Level 2** where a range of fully-calibrated cubes and tables are provided.
Cubes:

- 'Native', aka 're-binned', cubes have the footprint of the PACS IFU (see p. 4), which is a slightly irregular 5×5 grid of $9.4''$ spaxels. (The name is because they are the *spectrally* re-binned version of an earlier cube.) They are the recommended product for point sources and small sources, as the necessary flux correction tasks work on these cubes. To overcome the problem of the irregular spatial grid – which can be a problem when inspecting pointed or tiling observations of extended sources – interpolated cubes are provided as an additional to the re-binned cubes. Interpolated cubes are created via a interpolation of the fluxes of the re-binned cubes onto a regular sky grid of $3''$ spatial pixels.

- A range of mosaic cubes ('interpolated', 'projected', 'drizzled') are provided, depending on the mapping mode of the AOT and according to a set of standard observation parameter criteria which are outlined in the PACS Products Explained. For mapping observations, these cubes are a combination of the re-binned cubes from each raster position in the mapping sequence. For pointed observations, they are just spatially-resampled cubes. These mosaic cubes have a regular spatial grid, with spatial pixels of 1.5–$3''$ size, but note that this size varies with wavelength for some of the mapping observations. The PACS Products Explained gives the details of the spaxel sizes for the various cubes.

Tables:

- A table of point-source calibrated spectra for all pointed observations (provided regardless of what the source in the FoV actually is).

- A table of the spectra of the re-binned cubes (some external software can read the tables more easily than the cubes). For details of the layout of these tables, see the PACS Products Explained.

Level 2.5 can be found for the on-source observation of un-chopped range-scan AOTs for which the observer requested a linked off-source observation. The same range of Level 2 products can be found, but here the data have been background subtracted.

At Levels 2 and 2.5 there is a red and a blue version of each product, and a separate product for each wavelength range requested by the observer.

Some chop-nod pointed also SEDs have a **Level 3**: a concatenation of the Level 2 point-source tables, for both cameras and from all observations taken to cover the full SED of a single source.

The similarities and differences, and the prime purpose of the cubes and tables are explained in the PACS Products Explained. Advice on how to use the cubes, and details of the tasks that created them, can be found in the PACS Data Reduction Guide (spec) (chps 7, 8[point sources], 9[extended sources]).

Level 0	Raw data, formatted from the raw telemetry by an external pre-processing stage.
Level 0.5	Engineering conversions, timing and pointing information computed, bad-data masking, data organised in blocks. For SSOs the coordinate system is set so the object is in a fixed position on the sky at all times. Level 0.5 data are signal timelines, un-calibrated but with the first spectral and spatial conversions done.
Level 1	Glitch masking performed, and the data are organised into the first cube of the pipeline, with dimensions $5 \times 5 \times$[nr. readouts]. The signal of chop-nod AOTs are dark and background subtracted and for un-chopped AOTs are dark subtracted. Level 1 data are organised as timelines and are calibrated: Jy for un-chopped AOTs and 'telescopes' for chop-nod AOTs.
Level 2	Data are spectrally flatfielded and a second de-glitching performed. A regular wavelength grid is created for each cube and the signal spectrally resampled along this grid, to create 'native' (aka 'rebbined') cubes. For un-chopped line scans, the background is subtracted. For pointed and tiling observations, interpolated cubes are created. For mapping observations the cubes provided depend on the AOT, and this is explained later in this guide: the choices are drizzled, projected, and interpolated (the decision is made independently for the red and blue camera; the type of cube provided may not be the same in the two). The stddev/error array is computed. Re-binned cube tables are created from the re-binned cubes and point-source tables created for all pointed AOTs. Level 2 data have units of Jy/pixel, where the 'pixel' refers to the spaxel in the cube, which is a $9.4''$ spaxel for re-binned cubes, and a smaller (1.5–$3''$) for all other cubes.
Level 2.5	For un-chopped range scan observations with an associated off-source observation, the two observations are each reduced to Level 2. Extended processing then subtracts the off-source data from the on-source data to produce the same range of, background subtracted, products which are placed in the Level 2.5 of the on-source observation. If the observer did not request an off-source observation, the final level is Level 2. To know which off-source observations correspond so the on-source observations, consult the comments in the qualitySummary in the ObservationContext, or consult the list on the data products overview page
Level 3	This level is provided for pointed chop-nod observations of SED mode for which sufficient observations (two, sometimes three) were requested to cover the full PACS range (55–190 μm) of the source. The red and blue point source tables for all observations are concatenated into a single table. Consult the list on the data products overview page to know which obsids these are.
Calibration	The directory of calibration files used by the SPG pipeline.
QualitySummary	This contains flags and comments concerning issues with the observation. This is most easily read from the 'QCR' listed in the HSA search results tab.
BrowseProduct	Contains the standalone browse products (SBPs: see later).
BrowseImageProduct	The postcard that can be found on the HSA search results page can also be found here. The postcard is also available as a jpg file in the 1342... directory.

PACS spectrometer products in the Herschel Science Archive (HSA)

Any full observation can be downloaded from the HSA in a tarball as a complete Observation context. Individual pipeline levels can also be retrieved, and final-level cubes and tables are also provided as Standalone Browse Products (SBPs). The following tables list the folder structure and the FITS files that can be found in the unpacked tarball of a full observation, below the directory with the obsid as the name (1342...), excluding the engineering, housekeeping, and auxiliary directories and products.

Level 0 to 1 products

The Level 0–1 products are not science-quality and most users will never need to look at them.

<table>
<tr><th>Folder</th><th>Sub-folder</th><th>Filename pattern</th><th>Description</th></tr>
<tr><td>Level 0</td><td>HPSFIT[B|R]/herschel.pacs.signal.Frames</td><td>hpacs<OBSID>_00hpsfit[b|r]s_00_<NNN></td><td>Fitted time-line data</td></tr>
<tr><td></td><td>HPSRAW[B|R]/herschel.pacs.signal.Tramps</td><td>hpacs<OBSID>_00hpsraw[b|r]s_00_<NNN></td><td>Raw time-line data</td></tr>
<tr><td>Level 0.5</td><td>HPSFIT[B|R]/herschel.pacs.signal.Frames</td><td>hpacs<OBSID>_05hpsfit[b|r]s_<##>_<NNN></td><td>Fitted time-line data</td></tr>
<tr><td>Level 1</td><td>HPSFIT[B|R]/herschel.pacs.signal.Frames</td><td>hpacs<OBSID>_10hpsfit[b|r]s_<##>_<NNN></td><td>Fitted time-line data</td></tr>
<tr><td></td><td>HPS3D[B|R]/herschel.pacs.signal.PacsCube</td><td>hpacs<OBSID>_10hps3d[b|r]s_<##>_<NNN></td><td>First cube of the pipeline</td></tr>
</table>

<NNN> is a timestamp. Most PACS products are ‘sliced’, with one product of each type for each wavelength range requested in the observation. Slice numbers are indicated as ‘s_<##>’; at Level 0 there is only one slice. All products have a red and blue camera version, indicated by ‘[b|r]’ in the filename and ‘[B|R]’ in the directory name.

Level 2, 2.5, and 3 products

The science-use products at Level 2 and 2.5 are cubes and tables, varying in type according to the AOT, and at Level 3 there is only a spectrum table. The following table lists the products at these levels. All the products in this table are science-ready unless specified otherwise.

<table>
<tr><th>Folder</th><th>Sub-folder</th><th>Filename pattern</th><th>Description *AOT*</th></tr>
<tr><td>Level 2</td><td>HPS3D[B|R]/herschel.pacs.signal.PacsCube</td><td>hpacs<OBSID>_20hps3d[b|r]s_<##>_<NNN></td><td>earliest cube
not for science</td></tr>
<tr><td></td><td>HPS3DR[B|R]/herschel.pacs.signal.PacsRe-binnedCube</td><td>hpacs<OBSID>_20hps3dr[b|r]s_<##>_<NNN></td><td>native/re-binned cube</td></tr>
<tr><td></td><td>HPSTBR[B|R]/herschel.pacs.signal.PacsSpecTable</td><td>hpacs<OBSID>_20hpstbr[b|r]s_<##>_<NNN></td><td>re-binned cube table</td></tr>
<tr><td></td><td>HPS3DP[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs<OBSID>_20hps3dp[b|r]s_<##>_<NNN></td><td>projected cube</td></tr>
<tr><td></td><td>HPS3DI[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs<OBSID>_20hps3di[b|r]s_<##>_<NNN></td><td>interpolated cube
(Nyquist+range-scan,
all pointed and tiling)</td></tr>
<tr><td></td><td>HPS3DD[B|R] /herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs<OBSID>_20hps3dd[b|r]s_<##>_<NNN></td><td>drizzled cube
(line-scan+
Nyquist and oversampled)</td></tr>
<tr><td></td><td>HPSSPEC[B|R]/herschel.pacs.signal.PacsCentralSpectrum</td><td>hpacs<OBSID>_20hpsspec[b|r]s_<##>_<NNN></td><td>point-source table
(pointed)</td></tr>
<tr><td>Level 2.5</td><td>HPS3DRBS[B|R]/herschel.pacs.signal.PacsRe-binnedCube</td><td>hpacs_25HPS3DRBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN></td><td>native/re-binned cube</td></tr>
<tr><td></td><td>HPSTBRBS[B|R]/herschel.pacs.signal.PacsSpecTable</td><td>hpacs_25HPSTBRBS[B|R]S_ <RA>_<DEC>_<##>_v1.0_<NNN></td><td>re-binned cube table</td></tr>
<tr><td></td><td>HPS3DPBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs_25HPS3DPBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN></td><td>projected cube</td></tr>
<tr><td></td><td>HPS3DIBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs_25HPS3DIBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN></td><td>interpolated cube
(Nyquist+range-scan,
all pointed and tiling)</td></tr>
<tr><td></td><td>HPS3DDBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs_25HPS3DDBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN></td><td>drizzled cube
(line-scan+
Nyquist and oversampled)</td></tr>
<tr><td></td><td>HPSSPECBS[B|R]/herschel.pacs.signal.PacsCentralSpectrum</td><td>hpacs_25HPSSPECBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN></td><td>point-source table
(pointed)</td></tr>
<tr><td>Level 3</td><td>HPSSPEC</td><td>hpacs_30HPSSPEC_<RA>_<DEC>_v1.0_<NNN></td><td>point-source table
(pointed+chop-nod+SED)</td></tr>
</table>

<NNN> is a timestamp, <RA> and <DEC> are the coordinates. Most PACS products are 'sliced' (indicated with an 's' or 'S' at the end of the hps.../HPS... part of the filename), with one product of each type for each wavelength range, and the slice numbers are '<##>'. Level 3 is not sliced. All Level 2 and 2.5 products have a red and blue camera version, indicated by '[b|r]' in the filename and '[B|R]' in the directory name. If no AOT details are given in the Description column, the product is provided for all AOTs. The reason for the difference in the filenames between Level 2 and 2.5/3 is purely to fit in with the general *Herschel* convention.

Standalone Browse Products (SBPs)

The SBPs are taken from Level 2 and, if present, Levels 2.5 and 3. Where both Level 2 and 2.5 are present, remember that the Level 2.5 are background subtracted and have 'BS' in the directory and FITS file names. One type of cube is provided for each observation, depending on the AOT. This cube is created from the Level 2/2.5 cube of the same type, with one difference: the Level 2 cubes have a *non-equidistant* wavelength grid, while the SBP cubes have an *equidistant* wavelength grid (hence the 'EQ' in the filename). The difference is explained on p. 6.

All the products in this table are science ready.

<table>
<tr><th>Folder</th><th>Sub-folder</th><th>Filename pattern</th><th>Description AOT</th></tr>
<tr><td>browseProduct</td><td>HPSTBR[B|R]/herschel.pacs.signal.PacsSpecTable</td><td>hpacs<OBSID>_20hpstbr[b|r]s_<##>_<NNN></td><td>re-binned cube table (L2)</td></tr>
<tr><td></td><td>HPSTBRBS[B|R]/herschel.pacs.signal.PacsSpecTable</td><td>hpacs_25HPSTBRBS[B|R]S_<RA>_<DEC>_
<##>_v1.0_<NNN></td><td>re-binned cube table (L2.5)</td></tr>
<tr><td></td><td>HPSSPEC[B|R]/herschel.pacs.signal.PacsCentralSpectrum</td><td>hpacs<OBSID>_20hpsspec[b|r]s_<##>_<NNN></td><td>point-source table (L2)
(pointed)</td></tr>
<tr><td></td><td>HPSSPECBS[B|R]/herschel.pacs.signal.PacsCentralSpectrum</td><td>hpacs_25HPSSPECBS[B|R]S_<RA>_<DEC>_
<##>_v1.0_<NNN></td><td>point-source table (L2.5)
(pointed)</td></tr>
<tr><td></td><td>HPSSPEC</td><td>hpacs_30HPSSPEC_<RA>_<DEC>_v1.0_<NNN></td><td>point-source table (L3)
(pointed+chop-nod+SED)</td></tr>
<tr><td></td><td>HPS3DEQP[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>pacs<OBSID>_20hps3deqp[b|r]s_<##>_<NNN></td><td>projected cube (L2)
[Nyquist, oversampled]
+ range-scan</td></tr>
<tr><td></td><td>HPS3DEQPBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs_25HPS3DEQPBS[B|R]S_<RA>_<DEC>_
<##>_v1.0_<NNN></td><td>projected cube (L2.5)
[Nyquist, oversampled]
+ range-scan</td></tr>
<tr><td></td><td>HPS3DEQD[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs<OBSID>_20hps3deqd[b|r]s_<##>_<NNN></td><td>drizzled cube (L2)
[Nyquist, oversampled]
+ line-scan</td></tr>
<tr><td></td><td>HPS3DEQDBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs_25HPS3DEQDBS[B|R]S_<RA>_<DEC>_
<##>_v1.0_<NNN></td><td>drizzled cube (L2.5)
[Nyquist, oversampled]
+ line-scan</td></tr>
<tr><td></td><td>HPS3DEQI[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs<OBSID>_20hps3deqi[b|r]s_<##>_<NNN></td><td>interpolated cube (L2)
[tiling, pointed, all other]</td></tr>
<tr><td></td><td>HPS3DEQIBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube</td><td>hpacs_25HPS3DEQIBS[B|R]S_<RA>_<DEC>_
<##>_v1.0_<NNN></td><td>interpolated cube (L2.5)
tiling, pointed, all other</td></tr>
</table>

In the Description column, note that e.g. *[Nyquist, oversampled] + range-scan* indicates "for all Nyquist or oversampled mapping AOTs *that are also* range-scans". If no AOT details are given, the product is provided for all AOTs.

Highly-Processed Data Products

Some of the PACS spectroscopy observations have been specially processed by the instrument scientists of the HSC to produce 'highly-processed data products' (HPDPs). The HPDPs are available at the Herschel (PACS) Legacy Repository, and they will soon be served directly via the HSA. These are introduced in the PACS Products Explained, and each HPDP page has its own release note.

- Red leak spectra. PACS Spectrometer observations at wavelengths longward of 190 μm were not processed by the SPG pipeline. These data will be instead processed with a non-standard calibration scheme for the chop-nod observations, and a dedicated relative spectral response function. The spectral cubes feature calibrated order 1 emission lines (i.e. those that originated in the red spectral range, rather than in the leaking range) in the 190–206 μm range, while the continuum remains un-calibrated.

- **Blue un-calibrated range** *(not yet released)*. The range between 51 μm and 55 μm cannot be calibrated, however there were data taken in this range (either because it is in the parallel camera or because the observer specifically requested it). These data will be released as an HPDP without a flux calibration applied.

- On-source and Off-source cubes. In order to make it easier for users to inspect the off-source data to check for the presence of contamination (line emission, mainly), all the un-chopped line-scan and chop-nod observations will be processed to produce separate cubes for the off-source and on-source pointings. The release note can be found on the link above, but the data need to be downloaded via the HSA. Note that if you do find contamination in the off-source position, it may be necessary to re-reduce your data: read the release note for more information.

- **Pointing Offset Correction point-source spectra** (*not yet released*). For point sources observed with the chop-nod pointed mode, the point-source calibrated spectra produced by the Pointing Offset Correction (POC) script may be superior to those produced from the SPG pipeline, if there was a large pointing offset (i.e. the source is not in the centre) or a lot of pointing jitter during the observation. This script – which is an interactive pipeline script in HIPE – is currently being run on all observations of this mode, and the results – the spectra and the diagnostic data created by the pipeline – will be provided as an HPDP.

Calibration and Ancillary products

Also available from the Herschel legacy web-pages are: the calibration tree files and the ancillary products.

- The Calibration tree files, up to the final update PACS_CAL_78_0.

- Ancillary Data Products (ADP) are data (images, tables, etc.) generated in the course of the various phases of the Herschel mission which are not necessarily linked to a particular observation in the HSA. Some of the PACS ADPs are extracted from the products already available in the calibration tree attached to each observation. Included as ADPs are: astronomical calibration source models, beams, filter transmission functions, PACS on-board software, health monitoring and trend analysis data.

For a quick look at a PACS spectroscopy observation

The fastest way to look at a the data from a PACS spectroscopy observation is to open one of the Level 2 or 2.5 mosaic cubes (e.g. the projected or interpolate cube: HPS3DP[B|R] or HPS3DI]B|R]) in any cube viewing software. If your software cannot read the spectral grid in these cubes, open instead the cubes provided as SBPs, i.e. the equidistant cubes. Since the spectral and spatial grid in these cubes are regular, with all the relevant information held in the WCS, any standard cube viewer should be able to read the cube and allow for a spectral and spatial visualisation.

Alternatively, you can look at a single spectrum from a PACS observation by reading the data in the point-source table (HPSSPEC[B|R]) – from Level 3 or 2.5 if present (no observation has both these levels), otherwise from Level 2. The spectral data is contained in an extension called 'spectra', which is a table of wavelength, fluxes, and errors: the spectrum of the central spaxel (Jy/pixel) and two or three versions of the point-source corrected spectra (Jy), created from the re-binned cubes of the same Level. The table is explained in the PACS Products Explained. The columns 'wave' and 'centralFlux' give you the central spaxel's spectrum. The column 'pointSourceCen3x3Flux' contains the point-source calibrated spectrum created from the sum of the central 3x3 spaxels.

Recommended reading when wanting to know what products to look at/work on is the Product Decision Tree, which lays out the options when working with PACS data for different types of sources.

Data Analysis scripts in HIPE

A number of useful scripts have been provided in HIPE to work with PACS spectroscopy cubes, most of which start from products gotten from the HSA; no pipeline processing required. These include:

- Point source corrections (centred and off-centred sources separately)
- Creating cubes with different spatial pixel sizes; combining spatially- and spectrally-overlapping observations from different programmes. This can be useful when dealing with the line-scan mapping observations where the size of the spatial pixel is optimised for the beam-size at the wavelength of the cube (i.e. all observations with drizzled cubes). If a comparison of cubes with the same size of spatial pixels is necessary, it may be worth re-doing the necessary mosaicking task with this script. An additional use-case will be for tiling observations that had very large steps in the raster, even exceeding the size of a single pointing. The cubes provided in the observation may look "smeared out". Re-creating the projected cubes with a spaxel size set to $\geq 1.5''$ seems to work best for these observations.
- Convolving fitted-line maps
- Creating maps by fitting emission lines in cubes – either working from the mosaic cubes, or using the re-binned cubes and then mosaicking the resulting 2D maps

Source-specific advice

The fluxes in PACS spectrometer cubes are only fully calibrated for fully extended sources. Among others, this is ensured by an extended source correction (ESC) that is applied by the pipeline to correct for the non-uniform spatial response of the system. For any other sources, extra corrections are necessary to extract the true flux of the observed source in the field of the cube. This includes:

- Point sources centred in the FoV of a re-binned cube, and point sources offset from the centre of the FoV
- Semi-extended sources ($< 30''$ diameter)
- Irregular extended sources

HIPE tasks are available to apply the necessary corrections for most of these cases. A set of user notes have been written to explain what to do.

- Dealing with point sources. For point sources, point-source corrections are a must. This document explains what to do for point sources located within a few arcsec of the centre of the central spaxel of a re-binned cube, what to do for point sources that are offset by up to one spaxel, and what to do for very offset point sources. The options include using a single task to extract the spectrum and calibrate it, reducing the data from Level 0 using the "POC" pipeline to correct for pointing offsets and jitter, or modelling the offset source and then applying the derived corrections to the spectra extracted from the re-binned cubes.
- Dealing with semi-extended sources. For sources of no more than $30''$ full size and which are located in the central region of a re-binned cube, it is possible to apply semi-extended source corrections to the spectra extracted from the re-binned cubes. These corrections are based on a model or high-resolution image of the source. It is very highly recommended that these corrections are applied to all semi-extended sources.
- Dealing with extended sources. For fully-extended sources that have a flat surface brightness distribution over the FoV of a single re-binned cube (of no more than about 20% over the $47 \times 47''$ FoV of these cubes), no additional corrections are necessary, whether they were observed with the mapping or pointed mode.

  For sources that are not flat – they have a steep gradient or an irregular morphology – the data are not fully flux calibrated, because the ESC is not fully applicable to these sources. The non-uniform spatial response – that the ESC tries to correct for – means that the PACS IFU behaves not as a grid of contiguous $9.4''$ spaxels, but as one with $\sim 8''$ non-contiguous spaxels. The effect of this is corrected for in the point and semi-extended source correction tasks, and for fully-extended sources the ESC returns fully-calibrated spectra. However, it is *not* fully corrected for irregular extended sources: the necessary extended-source correction for such sources turns out to be highly dependent on the shape of the source and the pointing pattern of the observation, and hence could not be computed as part of the general flux calibration scheme of PACS. You can try to work out how much this affects your target by using the Forward Modelling Script, and this script is described in this document on "Dealing with extended sources". However, note that this script is still under testing and it is an expert use-case.

The cases discussed here are also the subject of **video tutorials** that can be found in the Herschel Academy YouTube channel. For those dealing with PACS data for the first time, and those with point, semi-extended, or extended sources, these tutorials are useful viewing.

Science readiness of the spectroscopy products

An observation downloaded from the HSA contains Level 2 (all observations), 2.5 (un-chopped range on-source observations), and 3 (chop-nod pointed SED observations). The Level 3 is a courtesy product, being a concatenation of Level 2 tables. A range of cubes and tables are provided in the Levels to service the range of AOTs that PACS spectroscopy offered to observers. The information in this guide explain which products are best for which type of AOT.

All products in Levels 2/2.5/3 are all science ready in the sense that it is almost never necessary to rerun the pipeline. *However, we stress here that the fluxes the PACS cubes are only correct for flat extended sources. For all other sources – point or small, off-centred, extended – it is important to consider the source-specific advice offered in above.*

All observations in the HSA have a qualitySummary in which any specific quality issues for the observation can be found; this can be most easily checked in the HSA search results page. The PACS Handbook includes extra advice about dealing with some quality issues. A list of general issues/problems/warnings about PACS spectroscopy products is available in the Data Products Known Issues public page.

Other issues to consider when working with PACS spectroscopy

- Any point or point-like source that is not fully centred in a spaxel on the re-binned cubes will develop (i) line shifts and (ii) a skew. This is a consequence of the image slicer design for the PACS spectrometer (where the infalling light is arranged along a slit before being directed to the grating). This will affect the spectral lines both from a single native spaxel (i.e. from a re-binned cube) and also from mosaicked or combined spaxels. See the PACS Handbook for more information.
- Do not over-interpret the morphology of sources from under-sampled observations: these data are not suitable for looking at structure at the limit of the spatial resolution, since the spatial *sampling* is poor.
- A second pass in the optics of the PACS spectrometer can cause a ghost image (e.g. spectral line) from one spaxel to appear on another spaxel. This occurs for all except the central column of spaxels. A table of the most common ghosts can be found in the PACS Handbook.
- First-pass spectral leakage can be seen in all spaxels. These, transfer continuum emission from one band to another, and the worse affected order-leakage regions (e.g. the 'red leak') have been cut out of the spectral range provided in the SPG products. However, you should also watch out for leakage of bright lines. This is documented in the PACS Handbook.
- The continuum uncertainty for un-chopped observations (see p. 9) is for each spaxel of each cube. Hence if combining spectra from a cube (e.g. as is done by the point-source correction task to produce its "c9" output), be aware that the accumulation of continuum uncertainties will then be very large indeed.
- If your off-source data are contaminated (i.e. there is astronomical emission in the off-source position), then it may be a recommendation that you re-reduce your data. This is explained in a Technical note that accompanies the OnOff HPDP, which can be found directly on here on HELL level 2.

Acronyms, links, references

AOT	Astronomer Observation Template, i.e. the observation request details
FMT	Forward modelling tool
FoV	Field of View
FWHM	Full Width Half Max
HELL	Herschel Explanatory Legacy Library
HPDP	Highly Processed Data Product (provided for some observations at the HSA)
HSA	Herschel Science Archive
HSC	Herschel Science Centre
IFU	Integral field unit
obsid	observation identification number (1342...)
PDRG	PACS Data Reduction Guide
POC	Pointing offset correction pipeline script
PSF	Point Spread Function ('beam' is the PSF as imaged by the detector and the map/cube-making process)
PV phase	Performance Verification phase of the *Herschel* mission
spaxel/spatial pixel	one patch of sky with a full spectrum; can be used to refer to the physical spaxel of the instrument, or a projected spatial pixel of a mosaic cube
RPE	Relative Pointing Error
RSRF	Relative Spectral Response Function
SNR	Signal-to-noise ratio
SPG	Standard Product Generation (automatic pipeline run at the HSC)
SSO	Solar System Object

AOT header keyword CSV file	http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/AOTMetaData.tar
Ancillary Data Products	http://archives.esac.esa.int/hsa/legacy/ADP/
Beams	modelled: http://archives.esac.esa.int/hsa/legacy/ADP/PSF/PACS/Modelled/
	measured: archives.esac.esa.int/hsa/legacy/ADP/PSF/PACS/PACS-S/
Calibration tree files	http://archives.esac.esa.int/hsa/legacy/cal/PACS/user/
HPDPs	http://archives.esac.esa.int/hsa/legacy/HPDP/PACS/
Off/on-source range scan obsids	http://herschel.esac.esa.int/twiki/pub/Public/Level-2_5Products/PACS_Spectrometer_Level2_5_v14.2.txt

Data Products Known Issues	http://herschel.esac.esa.int/twiki/bin/view/Public/DpKnownIssues
PACS overview page	https://www.cosmos.esa.int/web/herschel/pacs-overview
PACS Products Explained	https://www.cosmos.esa.int/documents/12133/996891/PACS+Products+Explained/
PACS Handbook	http://www.cosmos.esa.int/documents/12133/996891/PACS+Explanatory+Supplement/
PACS Data Reduction Guide (spec)	http://herschel.esac.esa.int/hcss-doc-15.0/print/pacs_spec/pacs_spec.pdf
Product Decision Tree	https://www.cosmos.esa.int/documents/12133/996891/Product+decision+trees
HELL	https://www.cosmos.esa.int/web/herschel/legacy-documentation-pacs
	(Level 1 and 2 contain the most relevant documents)
Dealing with Contamination TN	https://www.cosmos.esa.int/documents/12133/996891/Dealing+with+contamination

Pilbratt et al., 2010	Pilbratt, G. L.; Riedinger, J. R.; Passvogel, T, et al., 2010, A&A, 518, L1
Poglitsch et al., 2010	Poglitsch, A., Waelkens, C., Geis, N., et al., 2010, A&A, 518, L2