QUICK-START GUIDE TO HERSCHEL–PACS
THE PHOTOMETER

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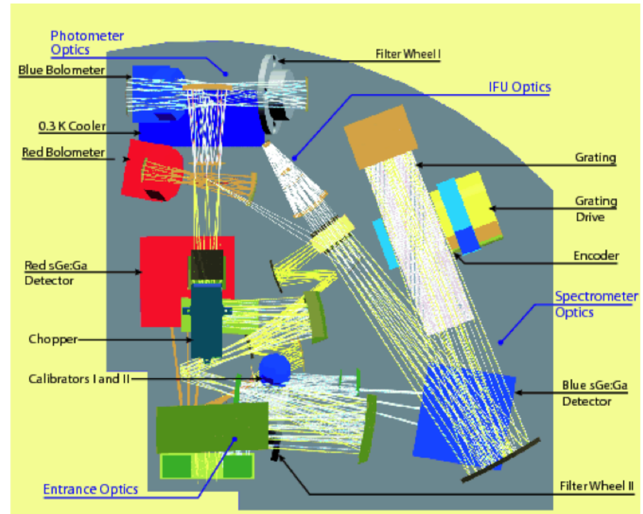
Contents

The PACS photometer

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. In this quick-start guide we deal with the PACS photometer.



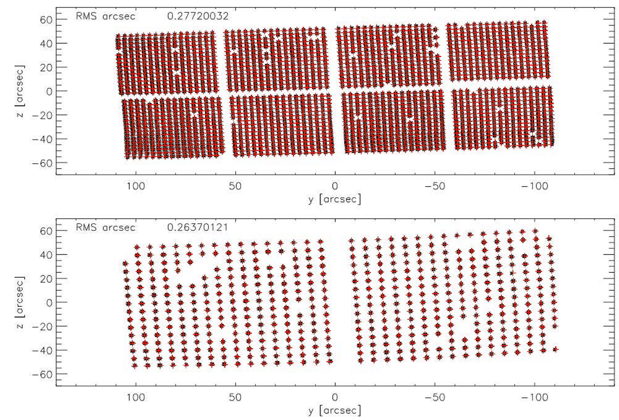
Some general characteristics of the PACS photometer are presented in the following table.

Band	Blue	Green	Red
Wavelength (μm)	70	100	160
R ($\lambda_0/\Delta\lambda_0$)	6.6	5.9	5.3
Instantaneous FoV	$3'.5 \times 1'.75$		
Beam FWHM^a ($''$)	5.6	6.8	10.7

a: The FWHM depends on the observing mode, values for the most common mode are given. See later for details.

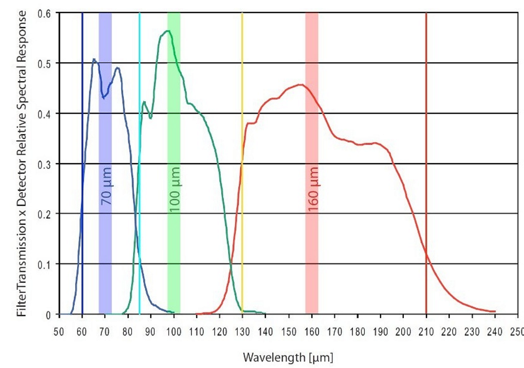
Photometer bolometer arrays.

The two bolometer arrays for the PACS photometer were composed of monolithic matrices of 16×16 pixels: 4×2 matrices for the short-wavelength camera (upper plot) and 2×1 for the long-wavelength camera (lower plot). The long-wavelength camera was coupled with the red filter, the short-wavelength camera was coupled with the blue and green filters; hence, any one observation could request the bands blue+red or green+red. The two photometer cameras had a different magnification to cover the same sky FoV with a different pixel scale ($3.2'' \times 3.2''$ and $6.4'' \times 6.4''$ for the blue and red arrays), which resulted in proper over-sampling of the beam in all final maps. On the bolometer array plots, each red cross is a detector pixel. Low-response (dead) pixels are the gaps.



Photometer bands.

The effective spectral response (product of filter transmission and bolometer detector absorption) for the three photometer bandpasses is shown to the right. The reference wavelength is indicated for each bandpass. The curves are available as a calibration product ('PCalPhotometer_FilterTransmission_FM_v1.fits')



Photometer beams

The beam of the PACS photometer was derived from observations of Vesta, Ceres, α Tau and α Boo, and observations of Neptune and Mars were used to probe the faint PSF wings. The main technical reference is Lutz (2015), which is summarised in the PACS Handbook.

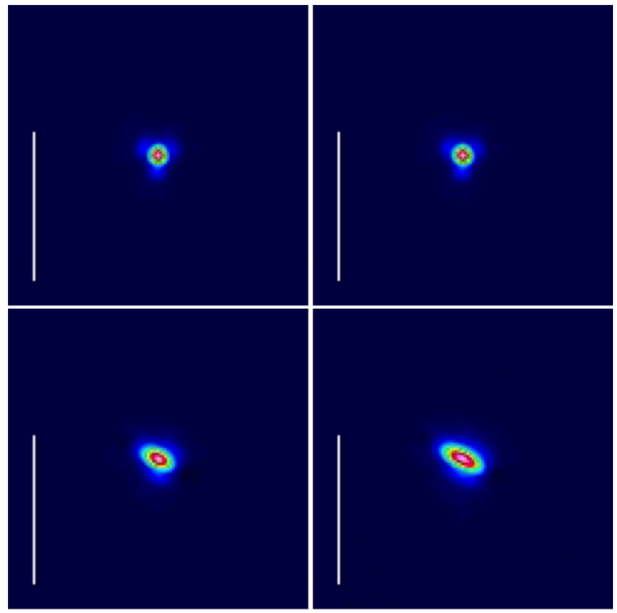
The beams at the most commonly-used medium scan speed (20″/s) and for the rarely-used slow speed (10″/s) are virtually identical. They are roughly round in the blue and green bands, but vertically (spacecraft Z direction) elongated in the red band. For fast (60″/s) prime-mode observations, a significant elongation along the scan direction is seen in all bands. For parallel-mode observations, a more pronounced elongation along the scan direction is also found, due to the lower time resolution of the blue detector array (8 frame averaging rather than 4); the shape of the red beam is the same in prime and parallel mode. This elongation means that the beam's shape on the sky depends on the scan angle – the elongation is along that angle. It is therefore important to note the scan angle and speed of an observation if knowing the PSF is necessary for your science. Another consequence of elongation is that on the combined scan maps (scan and cross-scan) which are provided by the pipeline, the combined beam has a cross-like shape.

The wings of the beam forms a tri-lobe pattern, at the level of up to 10% (in the blue) of the peak. At fainter levels, a knotty structure and some spikes appear. Note that the orientation of these 'ears' on the sky depends on the position angle the observation was performed at.

The photometer beam is, in fact, unique to each observation, as it depends on the observing strategy **and** on the map-making process. For point-source extraction or de/convolution tasks, it is *strongly* recommended to extract beams from the map proper, or from point-source data (e.g. calibration observations) that were reduced in a fully equivalent way. A set of beam images (a tarball of FITS files and an accompanying technical note) have been provided for download in HELL The beams are provided for the full range of AOT and band and have been rotated to a position angle of zero, but cover only a small number of scan angles – however, recall that it is the orientation of the elongation that changes with scan angle, not the shape. If using these images to compare to the shape of point sources in a PACS map, remember that the scan angle, speed, and position angle are all important to the shape of the beam (core and wings), and that most observations are combined scan+cross scan maps.

On the next page is a table of representative values of the FWHM (minor and major axis values) for a selection of scan speeds and for a single scan map or a combined scan+cross-scan map. Selected 70 μm beam images that demonstrate how the beam shape varies with scan speed and AOT are also shown. More images of the beam at various scan speeds, AOTs, bands, and cut levels (to show the wings and ears) are included in the PACS Handbook.

FWHM (″)	Prime 20″/s	Prime 60″/s	Parallel 20″/s		Parallel 60″/s	
	one scan		one scan	scan+cross-scan	one scan	scan+cross-scan
Blue	5.4×5.7	5.7×9.1	5.4×6.6	5.7×6.3	5.8×12.6	8.8×9.6
Green	6.7×5.9	6.8×9.8	6.6×7.5	7.0×7.4	7.0×13.3	9.7×10.7
Red	10.5×12.1	11.4×13.7	10.3×612.3	10.5×12.3	1..0×14.2	11.5×13.7



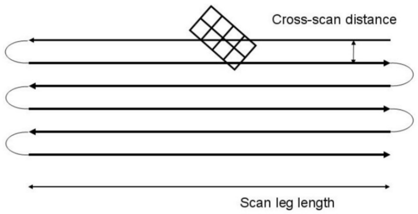
Effects of scan speed on the blue PACS beam. The PACS photometer PSF at 70 μm is shown for prime mode scan speeds of 10″/s (top left), 20″/s (top right), and 60″/s (bottom left). The additional smoothing because of the 5 Hz averaging in the blue channel for parallel mode is shown in the bottom right panel for speed 60″/s.

Photometer observing modes (AOTs)

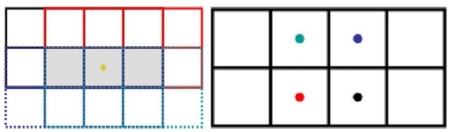
Three AOTs were offered throughout most of the mission: a standard scan-mapping AOT, a mini scan-mapping (point-source) AOT, and a SPIRE–PACS scan-mapping parallel mode. An additional point-source chop-nod AOT was used up to the end of the SD phase, but thereafter was exclusively for pointing and flux calibration observations. A chopped-raster AOT was also offered during the PV phase, but discontinued in favour of mini scan-mapping. The AOT release notes can be found on HELL, and the modes are described in the PACS Handbook.

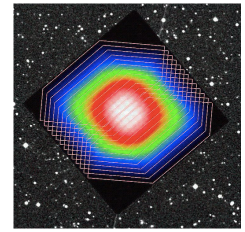
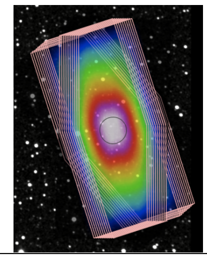
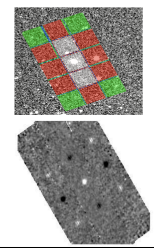
All photometer AOTs performed dual band photometry with the possibility to select either the blue (60–85 μm) or the green (85–125 μm) band for the blue channel, and the red band (125–210 μm) was always included. The two bolometer arrays provided full spatial sampling in each band.

The scan-map AOT. The telescope was commanded to scan over an observer-requested track across the sky, building up the coverage to obtain the desired sensitivity. A 6-leg sketch of a scan pattern is shown in the figure to the right. Two observations performed at orthogonal scan angles was the recommendation to result in a good sensitivity and even coverage. The scanning details could be set by the observer, although some parameters were fixed for the mini-scan map mode, which was optimised for a small area of uniform coverage. The final maps were created by projecting the signals from the detector (which was recording continuously while the telescope scanned the sky) on to a sky grid.



The chop-nod point-source AOT. This used a combination of the PACS chopper and telescope nodding to move the source on the detector array in a definite pattern, as illustrated to the right: the footprint of the blue detector array on the sky (left) and the chop-nod point-source pattern (right) produced on the detector. The colours reflect the four combinations of the nodding and chopping positions attained during the observing sequence: black: nodA chop1, red: nodA chop2, blue: nodB chop1, cyan: nodB chop2. The main advantage of the chop-nod AOT compared to the mini scan-map AOT was a tighter and more stable beam due to a lower RPE, but the sensitivity was notably inferior for the same observing time.



AOT details	
Scan map. This was the most commonly-used AOT. The number of scan legs, the leg length and separation, orientation (scan) angle, and repetition factor were freely selectable by the observer to obtain the desired map size and sensitivity. Slow (10″/s), medium (20″/s) and fast (60″/s) scan speeds were offered; the slow speed was discontinued after the PV phase. The medium scan speed was the most popular, the fast scan speed was aimed at very large sky areas, at some cost to sensitivity and beam shape. Most observers performed two scans as separate but linked observations, with scan angles of 45^o for the 'scan' and 135^o for the 'cross-scan'. The area of uniform coverage is the overlap between the two, as shown to the right for a small scan map. A 'coverage' dataset can be found in all maps.	
Mini scan map/point-source photometry. This used the standard scan map AOT but with some parameters fixed. It was aimed at point sources, with a uniform coverage over a 50″ circular piece of sky. The scan angles were fixed to 70^o and 110^o, and the scan leg length and separation also fixed within a small range. Compared to the chop-nod point-source AOT (below), the mini-scan map AOT gave a more homogeneous coverage of a larger area, without confusion by 'negative beams', and a better characterisation of the source vicinity. The image shows the coverage for a typical scan and cross-scan performed with this AOT.	
Chop-nod point-source. This AOT was mainly for calibration observations. The PACS chopper displaced the source on-array by 50″, corresponding to the size of about 1 blue/green bolometer matrix or half a red matrix. and telescope nodding to move the source around the detector. The nodding was performed by a satellite movement of the same amplitude but perpendicular to the chopping direction. The four combinations of the nodding and chopping positions resulted in data with four positive and four negative images of the source, and the combination of these (performed by the pipeline) produced the final point-source image (at the centre). The image shows a coverage map and image for this AOT.	
Parallel Mode. This AOT was for scan mapping with SPIRE and PACS at the same time on the same patch of sky. With a fixed 21′ separation of the PACS and SPIRE footprints in the *Herschel* focal plane, only large maps had sufficient common overlap in this mode. The medium and fast scan speeds were offered. The orientation angle was fixed to the optimum value for SPIRE – 42.4^o and $317.6(-42.2)^o$ (scan and cross-scan). Due to the reduced telemetry rate, eight frames were averaged on-board rather than four. For all other aspects the PACS instrument set-up was identical with the prime mode. As this AOT was optimised for SPIRE, the sensitivity of the PACS maps is lower than could be achieved with the PACS prime mode.	

Photometer calibration and calibration uncertainties

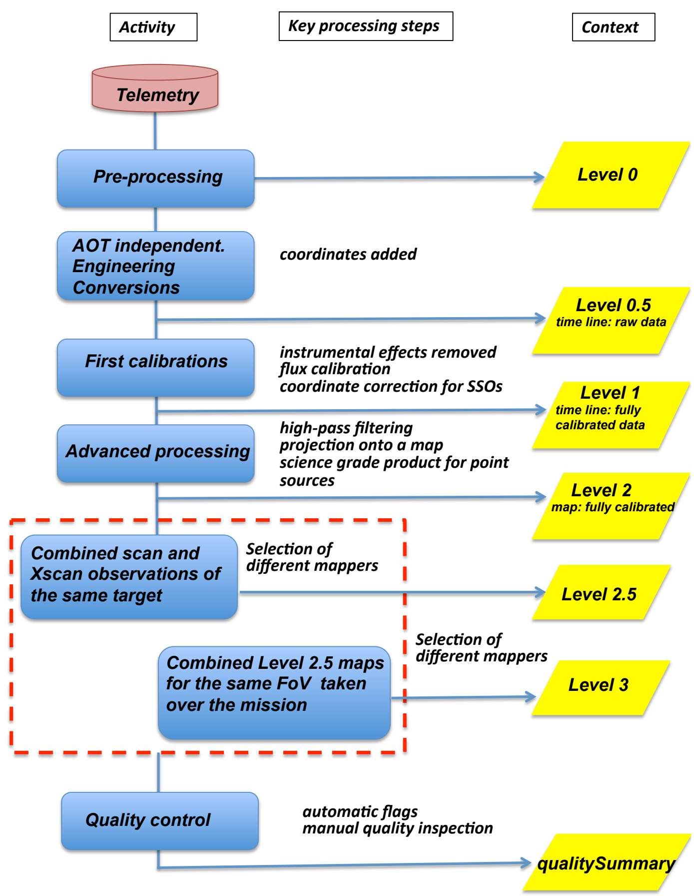
The flux calibration for PACS is based primarily on late-type giants (five fiducial stars). Bright asteroids and and planets were used to verify the non-linearity corrections determined in the lab. The models and the photometer calibration are discussed in the PACS Handbook. It should be noted that PACS maps are not absolutely scaled because of the way the mappers work in removing the background: all measurements must be made with respect to the map background (whatever its value is). PACS maps have units of Jy/(map pixel), and measurements of point *and* extended sources can be made directly from the maps (although some map types are more suited to point sources, as explained later).

Point-source aperture corrections for the various scan speeds and the prime/parallel mode can be found in the calibration file 'PCalPhotometer_ApertureCorrection_FM_v4.fits' and are tabulated in the PACS Handbook. Colour corrections for various source temperatures and SED (valid for point and extended sources), and conversions between PACS and selected other instruments, can also be found in the PACS Handbook.

Calibration uncertainty	Comment
Absolute: 5% (for all), +2% (for bright)	Dominant uncertainty arises from the accuracy of the model fluxes, plus a contribution from the non-linearity correction for bright sources. This uncertainty is correlated across the three bands.
Relative: 1% (B,G), 3% (R)	Reproducibility measurements of the same sources throughout the mission. Includes: flatfield, pointing jitter, instrument corrections, evolution of the telescope background, mapper methods.
Additional uncertainty information	
Error maps ('stDev' or 'error' extension in the FITS files)	PACS maps have two sources of error: the noise per map pixel, arising from the signal of each detector pixel that contributes to the map pixel; the uncertainty related to how the mapper works ('correlated noise'). For the three types of maps provided for PACS, the following should be noted: HPF+photProject provides an 'stDev', which is the standard deviation of the detector readouts falling on to each sky pixel, and an 'error' which is estimated via the coverage using an empirical calibration established on cosmological fields; Unimap generates an 'error' that is computed within the framework of the mapper; Jscanam provides a 'stDev' extension, which can be considered a good representation of the map noise since Jscanam maps are created as projected timelines. See the PACS Handbook for more detail.
Photometry	Often the dominant source of photometric error on PACS maps is the scatter in the background. It is recommended that this scatter is measured with apertures of the same size as used for the astronomical source (whether point or extended).

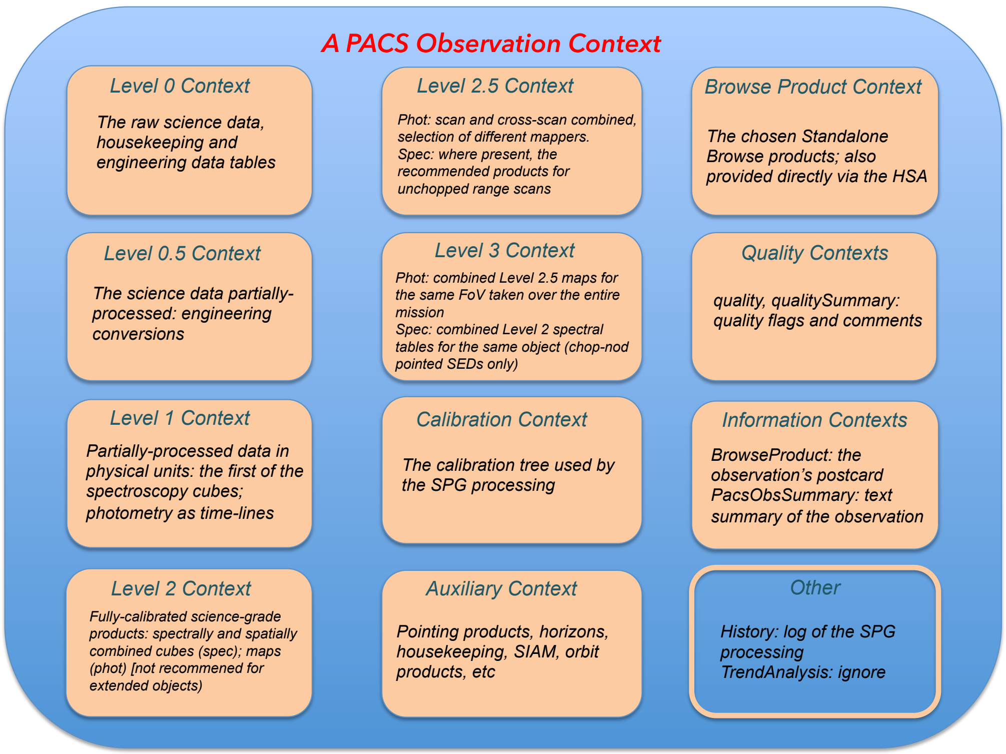
Photometer pipeline

A step-by-step description of the scan-map pipeline is presented in the PACS Data Reduction Guide (phot) and summarised in the PACS Handbook. The pipeline is run on all scan-map observations to produce Level 1 products, and the HIPE-specific highPassFilter (HPF: to remove the background) and photProject (to project the detector data on to a sky grid) tasks are then run, producing a red and a blue Level 2 map. This is the end for any scan-map programme that requested only one scan direction AOT on the source. For the majority of observations that provided linked scan and cross-scan AOTs, Level 2.5 maps are produced directly from the combined Level 1 data of the two observations using the mappers: (i) HPF+photProject; (ii) Jscanam (Graciá-Carpio, Wetzstein, Roussel, 2015), the HIPE implementation of the IDL mapmaker Scanamorphos (Roussel, 2013); and (iii) Unimap (Piazzo et al., 2015), which is spawned from HIPE. Level 3 maps are produced for observations that have the same AOT and happen to overlap on the sky, producing the deepest maps. A schematic overview of the scan-map pipeline is given to the right. For a comparison of the various mappers to each other, and a comparison of PACS maps to those from other instruments, see the documents on HELL. Chop-nod observations are reduced with a separate pipeline which is not explained here. The various pipelines can be found in HIPE, as well as scripts to: perform point-source photometry or convolve images.



Data structure for PACS photometer: 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, the reduced Levels (0 to 3), the calibration tree used to reduce the data by the automatic ('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.



High level description of the different levels in the PACS photometry Observation Context

Level 0	Raw data, formatted from the raw telemetry by an external pre-processing stage.
Level 0.5	Engineering conversions, pointing information computed, data organised in blocks and internal calibration block removed. Level 0.5 data are the uncalibrated, uncorrected timelines.
Level 1	Data taken during telescope slews and from bad detector pixels are masked out, as are cross-talk and saturation. Flatfielding and non-linearity corrections applied. For SSOs the coordinate system is set so the object is in a fixed position on the sky at all times. Level 1 data are still timelines but are flux calibrated (units of Jy).
Level 2	The timeline detector data from Level 1 are projected on to a sky grid (via the highPass filtering + photProject tasks): one red and one blue map for each observation. Data glitches are masked out, the source masked, timelines cleaned with the 'highPass filtering' task and the data projected using the photProject task. Level 2 data are maps in units of Jy/(map pixel). Level 2.5 data, where present, should be used in preference to the Level 2. Note that Level 2 maps are not suitable for use with extended sources.
Level 2.5	For observations with a scan AOT and cross-scan AOT, the Level 2 maps are combined into a single (red and blue) map. Pixel sizes for all maps are $3.2''$ for blue/green parallel mode AOTs and $1.6''$ for the blue/green prime mode, and $3.2''$ for all red band data. In addition, the Jscanam and Unimaps tasks are run on the scan and cross-scan Level 1 data to produce directly Level 2.5 maps. Level 2.5 data are maps in units of Jy/(map pixel). The Jscanam and Unimap maps are suitable for use on point and extended sources, but the photProject maps only for point sources.
Level 3	For observations that are otherwise unrelated (e.g. were not part of the same programme) but overlap on the sky and have the same AOT, a mosaic is created from all the available observations. These maps are superior to Level 2.5 in terms of sensitivity. What combination of blue, green, and red maps are present depends on the common bands in the observations that were combined.
Calibration	The calibration files used by the SPG pipeline. This directory is located at the level of the obsid directory, and organised as subdirectories with calibration product names.
QualitySummary	The qualitySummary will (eventually) be present for every observation. It contains flags and comments concerning issues with the observation. Unfortunately it is difficult to access this from the FITS file in this directory, but a human-readable version can be found in the HSA search results tab.
BrowseProduct	Contains the standalone browse products (SBPs), which are the Level 2.5 Jscanam maps except for observations with only one scan direction, where they are the Level 2 maps.

PACS photometer 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 maps are also provided as Standalone Browse Products (SBPs). The table here lists the folder structure and all possible FITS files that can be found in the unpacked tarball of a full observation, below the directory with the obsid (1342...) as the name (excluding the engineering, housekeeping, and auxiliary directories and products).

<table>
<tr><th>Folder</th><th>Sub-folder</th><th>Filename pattern</th><th>Description</th></tr>
<tr><td>browseImageProduct</td><td></td><td>hpacsbrowseimage_<NNN></td><td>The postcard</td></tr>
<tr><td>browseProduct</td><td>blue_Jscanam_map
blue_Jscanam_map
red_Jscanam_map
blue_projected_map
red_projected_map</td><td>hpacs_25HPPJSMAPB_blue_<RA>_<DEC>_00_v1.0_<NNN>
hpacs_25HPPJSMAPB_green_<RA>_<DEC>_00_v1.0_<NNN>
hpacs_25HPPJSMAPR_<RA>_[p|m]<DEC>_00_v1.0_<NNN>
hpacs<OBSID>_20hppmapb_00_<NNN>
hpacs<OBSID>_20hppmapr_00_<NNN></td><td>Level 2.5 SBP

Level 2 SBP</td></tr>
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/herschel.pacs.signal.Frames</td><td>hpacs<OBSID>_00hppavb<b|r>s_00_<NNN></td><td>timeline data</td></tr>
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<tr><td>Level 1</td><td>HPPAVG<B|R>
/herschel.pacs.signal.Frames</td><td>hpacs<OBSID>_10hppavb<b|r>s_00_<NNN></td><td>timeline data</td></tr>
<tr><td>Level 2</td><td>HPPMAP<B|R></td><td>hpacs<OBSID>_20hpppmap<b|r>_00_<NNN></td><td>projected maps</td></tr>
<tr><td>Level 2_5</td><td>HPPHPFMAPB
HPPHPFMAPB
HPPHPFMAPR</td><td>hpacs_25HPPHPFMAPB_blue_<RA>_<DEC>_00_v1.0_<NNN>
hpacs_25HPPHPFMAPB_green_<RA>_<DEC>_00_v1.0_<NNN>
hpacs_25HPPHPFMAPR_<RA>_<DEC>_00_v1.0_<NNN></td><td>projected maps
(scan+cross-scan)</td></tr>
<tr><td></td><td>HPPJSMAPB
HPPJSMAPB
HPPJSMAPR</td><td>hpacs_25HPPJSMAPB_blue_<RA>_<DEC>_00_v1.0_<NNN>
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hpacs_25HPPJSMAPR_<RA>_<DEC>_00_v1.0_<NNN></td><td>Jscanam maps
(scan+cross-scan)</td></tr>
<tr><td></td><td>HPPUNIMAPB
HPPUNIMAPB
HPPUNIMAPR</td><td>hpacs_25HPPUNIMAPB_blue_<RA>_<DEC>_00_v1.0_<NNN>
hpacs_25HPPUNIMAPB_green_<RA>_<DEC>_00_v1.0_<NNN>
hpacs_25HPPUNIMAPR_<RA>_<DEC>_00_v1.0_<NNN></td><td>Unimap maps
(scan+cross-scan)</td></tr>
<tr><td>Level 3</td><td>HPPJSMAP<B|R> and
HPPUNIMAP<B|R></td><td>same as Level 2.5 but ‘30’ in place of ‘25’</td><td>multiple obsids combined</td></tr>
</table>

<RA> is the hour+minute, <DEC> is the <p|m>degree+arcminute. <NNN> is a timestamp. The SBPs provided are Level 2.5 maps unless only Level 2 is present. All observations have a red, and either a blue or green map, however only Level 2.5 includes the words ‘green|blue’ in the name. The bands present at Level 3 depends on the common bands in the combined observations.

Science readiness of the photometry products

The Level 2.5 Unimap and JScanam maps (the latter also being SBPs) are science-ready products that can be used for point sources or extended emission. They are standard FITS files with extensions: image, coverage, error or stDev, and some mapper-specific extensions(explained in the PACS Handbook). The HPF+photProject maps can be used only for point-like emission, and those in Level 2.5 should be used in preference to those in Level 2, as the sensitivity will be higher (being combined scan+cross-scans). If Level 3 maps exist, these can be adopted instead of the Level 2.5 maps because of the better SNR (being the combination of several Level 2.5 products). For aperture photometry, the aperture and colour corrections as published in the links given on p. 8 (and in the PACS Handbook) should be used. It should also be noted that PACS maps are differential maps, where the absolute level is undefined as it is removed by the map-making process. Hence it is not a worry if the background level is negative. All measurements should be made with respect to the (source-free) background on the maps.

Detailed lists of issues/problems/warnings about PACS photometry products is available in the Data Products Known Issues public page. *This page should be consulted as the information is not repeated here.* 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.

Acronyms, links, references

AOT	Astronomer Observation Template, i.e. the observation request details
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)
HPF	High-pass filter (a HIPE task to clean the detector timelines before projecting them on to a sky grid)
HSA	Herschel Science Archive
HSC	Herschel Science Centre
obsid	observation identification number (1342...)
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
RPE	Relative Pointing Error
SBP	Standalone browse product
SNR	Signal-to-noise ratio
SPG	Standard Product Generation (automatic pipeline run at the HSC)
SSO	Solar System Object

Data Products Known Issues	http://herschel.esac.esa.int/twiki/bin/view/Public/DpKnownIssues
HELL	https://www.cosmos.esa.int/web/herschel/legacy-documentation-pacs (Level 1 and 2 contain the most relevant documents)
PACS Data Reduction Guide (spec)	http://herschel.esac.esa.int/hcss-doc-15.0/print/pacs_spec/pacs_spec.pdf
PACS Data Reduction Guide (phot)	http://herschel.esac.esa.int/hcss-doc-15.0/print/pacs_phot/pacs_phot.pdf
PACS Products Explained	http://herschel.esac.esa.int/hcss-doc-15.0/print/pacs-ppe/pacs-ppe.pdf
PACS Handbook	http://www.cosmos.esa.int/documents/12133/996891/PACS+Explanatory+Supplement/ 3ef39666-3ad3-4493-a81e-2c302d45b98e
Scanamorphos	http://www2.iap.fr/users/roussel/herschel/
Unimap	http://infocom.uniroma1.it/unimap/docs.html

Graciá-Carpio, Wetzstein, Roussel (2015)	https://arxiv.org/abs/1512.03252
Lutz, 2015	http://herschel.esac.esa.int/twiki/pub/HSC/PACSLevel1/bolopsf_22.pdf
Piazzo et al., 2015	Piazzo, L., Calzoletti, L., Faustini, F., et al., MNRAS, 2015, 447, 1471
Roussel, 2013	Roussel, H. 2013, PASP 125, 1126
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