Deliverable D2.1

H2020 COMPET-05-2015 project "Small Bodies: Near And Far (SBNAF)"

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Objectives: To produce expert-reduced Herschel data of primary focus targets: (a) of large TNOs (photometric and lightcurve observations); (b) MBAs (science and calibration observations); (c) dedicated NEA observations. To collect auxiliary infrared data from previous missions (Spitzer, Planck, WISE, Akari, IRAS, ISO, MSX) and published ground-based mid-IR, submm, millimetre observations and to prepare data for integration in a unique database. To create a database of infrared observations of all SBNAF targets (TNOs, MBAs, NEAs) with the option for extension to larger object samples.

Description of deliverable

D2.1 Herschel tools: Final set of tools and methods for Herschel/PACS moving target data reduction

Contents

1 Introduction

This document describes the delivery of the final set of tools and methods for the data reduction of moving target observations performed with the PACS photometer instrument (Poglitsch et al., 2010) of the Herschel Space Observatory (Pilbratt et al., 2010). It includes reduction scripts optimized for moving targets that are fine-tuned depending on the object's brightness, apparent motion, and background structures. We perform corrections for positional uncertainty due to telescope pointing and errors in source coordinates (source- and background matching technique) and produce combined data products with background elimination (differential, sky-subtracted, double-differential images). We provide tools for photometry and for the determination of photometric uncertainties.

A summary of Herschel Solar system object observations is given in Müller & Vilenius (2014); an overview of Herschel trans-Neptunian object observations (the "TNOs are Cool: a Survey of the trans-Neptunian region" Open Time Key Program) can be found in Müller et al. (2009). Observing and data reduction strategies related to this key program are summarized in Kiss et al. (2014). A full list of these observations is attached to this documentation. In this documentation we describe reduction steps and data products related to Herschel/PACS observations. For Herschel/SPIRE measurements of Solar system targets we use expert reduced data (see e.g. Fornasier et al., 2013).

2 Chop-nod observations

While the principal science observation mode with the PACS photometer is the scan map with the telescope scanning along parallel legs covering the map area (see Sect. 3) the *chopped point-source photometry* mode was also maintained throughout the mission. The chop-nod mode was used for science observations early in the mission and later only as calibration mode for observatory pointing calibration, which allowed a more accurate source position determination than scan mapping, and a low cost independent flux calibration check on the same celestial standards, including planets and asteroids (Müller et al., 2016). In total 2200 observations ($\sim$200 hours of observing time) have been executed in this mode.

For the chop-nod observations we use the standard HIPE reduction script in the case of all targets (near-Earth, main belt, and trans-Neptunian objects). We apply default settings and correct for the apparent motion of the targets. The fluxes of the targets are also determined in HIPE, and the HIPE-provided aperture (or encircled energy) corrections are used to obtain the final fluxes of the targets. A time dependent flux calibration for this observing mode is discussed in Nielbock et al. (2014). Details of the chop-nod data reduction steps are aslo discussed in Müller et al. (2010).

3 Data reduction pipeline for scan map observations

We use a modified version of the PACS pipeline for basic data reduction of scan-maps, producing single images per OBSID, from raw data to Level-2 maps (for the definition of the Herschel/PACS data product levels, see the PACS Observer's Manual). We applied the following main parameters in HIPE (for a summary of the PACS photometer scan-maps calibration, see Balog et al., 2014):

- Raw data and auxiliary information are obtained directly from the Herschel Science Archive via the getObservation() task.
- Slews are selected on scan speed with a limit parameter of *limits=10.* (e.g. between 15 and 25″ s^{-1} for 20″ s^{-1} scan speed).
- High-pass filter width of 8, 9 and 16 are used at 70, 100 and 160 μm, respectively – (high pass filter width sets the number of frames [2n+1] used for median subtraction from the detector timeline; see Popesso et al., 2012 and Balog et al., 2014, for a detailed description of the method).
- Masking pixels above 2-sigma, and at the source position with 2xFWHM radius
- We apply second level deglitching with nsigma=30, the sigma-clipping parameter of this deglitching method working on the map level (see the PACS Data Reduction Guide for more details).

Signal drift correction via the *scanamorphosBaselinePreprocessing()* task can be applied on the data in two ways, either using a fit algorithm (forceFitSubtraction=True) or simply masking the first frames of the observations. When the second option (forceMasking=True) is applied to typical scan map observations of faint targets, a significant part of the measurement is lost that results in a too low signal-to-noise ratio for the final maps. Therefore we do not use this option for scan map observations.

We apply the drizzle method to project the time-line data and produce the single maps using the *photProject()* task in HIPE, with a pixel fraction parameter of 1.0 in most cases.

For faint targets (typically below 100 mJy) we use pixel sizes of 1.″1, 1.″4 and 2.″1 in the PACS 70, 100 and 160 μm bands, respectively, that allows an optimal sampling of the respective point spread functions. For brighter targets the application of larger pixels (e.g. the default pixel size of 1 and 2″ for the blue and red detectors, respectively) provides identical results. In the case of standard pixel sizes final fluxes are obtained used the standard aperture correction factors in HIPE.

Out targets can be divided into three main groups: Near-Earth asteroids, main belt asteroid and trans-Neptunian objects (including Centaurs). The three main group also defines the typical apparent velocities of the targets, as trans-Neptunian objects move with a speed of ∼1 ”/h, while main belt and near-Earth asteroid have typical apparent velocities of >1 '/h. This means that main belt and near-Earth asteroids moves a distance several times the width of the PACS point spread function during a typical observation, while this displacement is usually negligible in the case of a trans-Neptunian object. This drives the solar system object tracking correction strategy of our data reduction: the correction is applied in the case of near-Earth and main belt asteroids in most cases, while it is not applied for trans-Neptunian object for background elimination purposes, as described in detail below. In some cases special observing conditions allowed for background correction for near-Earth asteroids, too. These special cases are going to be discussed individually at the respective deliverable (D2.2).

Determination of the photometric uncertainty in scan-map maps can be performed using the implanted source method. We provide a detailed description and the tools for this procedure in this deliverable (see Sect. 5.2). An alternative tool uses the pixel flux distribution in some selected sky areas and corrections using some scan-map parameters (high-pass filter width, pixel fraction parameter of the back projection, etc.) to obtain the final uncertainties (Klaas & Linz, 2016).

4 Data reduction of "TNOs are Cool!" mini-scanmaps

4.1 General description

Data reduction of slow-moving targets (typical apparent speed of ∼1 arcsec/h) allows a for an optimised background elimination in the case of properly designed observations. Objects with these apparent speeds are typically trans-Neptunian objects or Centaurs and the vast majority of them were observed in the framework of the "TNOs are Cool!" Open Time Key Program (PI: T. Müller, see Müller at al., 2009), using a well-defined observing strategy that allowed ideal background elimination (see also Kiss et al., 2014): the target was observed at two epochs, usually referred to as visit-1 and visit-2. The time between the two visits was set in a way that the target moved ∼30″with respect to the sky background that allowed us to use observations at the two epochs as mutual backgrounds. Observations at a specific visit also included scan/cross-scan observations in the same band, and usually observations in both possible PACS photometer filter combinations (70/160 and 100/160 μm, see also Fig. 1.).

In the case of these observations we do not correct for the apparent motion of the target to allow for an optimal background subtraction. In these cases, as a further step in our data reduction after the production of Level-2 maps using the HIPE script described above, we combine the single maps obtained in visit-1 and visit-2 with the aim to reduce the effect of the confusion noise due to the sky background. We produce the following image products:

- Co-added images (from the Scan-A and Scan-B images of the same, single visit)
- Differential images (from the co-added images, DIFF). Optimal coordinate offsets are determined with the "background matching" method
- Double differential (DDIFF) images, created from the differential images, using "source matching" to determine the ideal offsets

The main outline of these data reduction steps are presented and illustrated in Kiss et al. (2014). Here is give a summary and a detailed description of the procedure and functions used for these purposes. All data processing steps after Level-2 maps are performed in IDL[1].

Co-added images: Co-added images are generated using the maps of the individual OBSIDs in a specific band and in a single visit. In the case of both the blue and the green band we co-add two maps, the Scan-A and Scan-B images (B1 = B1A+B1B, G1 = G1A+G1B, etc., according to the scheme presented in Fig. 2). In the red band, all the four red maps (taken in parallel with blue/green and scan/cross-scan) are co-added (R1 = RB1A+RB1B+RG1A+RG1B, etc.). This processing step is performed using the *COADD* procedure (see below). The co-added images are the bases of the further processing steps and data products.

[1] Interactive Data Language, ITT Visual Information Solutions

Supersky-subtracted images: To create the so-called supersky-subtracted images first a background map is generated using the single maps. To do this we "mask" the target in each single map and co-add the maps in the sky coordinate system. This step produces a background map without the target. The background map is subtracted from the single maps producing background-subtracted single maps. Finally the background-subtracted maps are co-added in the target frame, producing the final combined map on which photometry is performed (this method has previously been described in detail and demonstrated with sample images in Santos-Sanz et al., 2012). A feature of this method is that at the masked locations the signal-to-noise ratio is lower than at the other parts of the image, since only the data of a single visit can be used here. The supersky-subtracted maps are produced by the *CREATE_SUPERKSKY_MAP* procedure.

Differential images and background matching: Background matching is used to correct for the small offsets in the coordinate frames of the Visit-1 and Visit-2 images when obtaining the differential image, which is simply the difference of the combined Visit-1 and Visit-2 images in the respective bands (BDIFF = B1–B2, etc., see also Fig. 1). Incorrect offsets can easily be identified by the appearance of positive/negative spot pairs and in the increase of standard deviations in selected areas on the differential maps. The offset to be applied can be determined using images of systematically shifted coordinate frames (created by the *CREATE_SHIFTED_MAPS* procedure) and then determining the offset which provides the smallest standard deviation of flux values in a pre-defined coverage interval or image area (typically $0.3 < \mathrm{coverage} < 0.9$, and using the *NOISE_CHECK_RUN* procedure). Our tests have proved that the same offset is obtained using any of the three PACS bands, however, in most cases the offset can be most readily determined using the 160 μm images, due to the strong sky background w.r.t. the instrument noise.

Double-differential images: A double-differential (DDIFF) image is made of the DIFF image of a target at a specific wavelength (see the *CREATE_DDIFF_MAPS* procedure below). The disadvantage of the DIFF image is that the images of the target appears as two separated beams (one positive and one negative), corresponding to the two visits. To produce a DDIFF image, first the DIFF image is "folded" (multiplied by -1). The folded image is shifted in a way that the location of the two positive beams of the target match on the original and the folded image. Then, the original and the folded/shifted DIFF images are co-added:

$$DDIFF(\underline{x}) = DIFF(\underline{x}) - DIFF(\underline{x} + \underline{\theta}) \quad (1)$$

where the optimal offset $\underline{\theta}$ is determined with the source matching method (see below). The DDIFF image contains a positive beam with the *total flux* of the target and two negative beams at the sides with "half" of the total flux It is a clear advantage of this method that the photometry can be performed on a single beam, and one does not have to combine the flux of two beams as in the case of the DIFF images. In the case of the DDIFF images the noise is increased by a factor of $\sqrt{2}$ when compared to the corresponding DIFF image, and flux variations between the two visits are flattened out. However, the signal-to-noise of the target is improved by $\sqrt{2}$ with respect to a single DIFF image which is very important in detecting faint targets. This method has proved to provide the best performance in the detection of very faint sources (<2 mJy at 70 μm), superior to the DIFF or SSKY images.

Source matching: Background matching (see above) provided offsets for coordinate frame differences in the two visits, but positional differences may still remain due to e.g. not well known positions of the target, and wrong offsets lead to distorted shapes of the target image when the images of the two visits are combined to obtain double-differential images. "Source matching" (see the *PLOT_SHIFTED_CONTOUR_MAPS* procedure below) determines the optimal offset ($\underline{\theta}$) that the original and folded DIFF images have to be shifted with to obtain the best matching of the centroids of the targets when we combine them to produce the DDIFF images. Typical offsets are a few arcseconds, we use the $\pm 4''$range both in R.A. and DEC to determine the offset. We demonstrate the method in Fig. 1 for Ixion. For relatively bright targets (a few tens of mJy) the source matching correction typically increase the flux by $\lesssim$10 per cent compared to the uncorrected case – in these cases the optimal offsets are in the order of $2''$. However, to detect very faint targets, source matching is a necessary step to detect the target at all.

4.2 List of functions:

COADD (procedure):

- **Description:** Co-adds Level-2 maps based on the WCS information of the FITS headers
- **Syntax**: COADD, FILES=files, FILE_OUT=file_out, [, /HIPE10]
- **Obligatory keywords**:
  - FILES=files: name of the input files in the form of a string array
  - FILE_OUT=file_out: name of the output file (string)
- **Optional keywords**:
  - HIPE10: set this keyword if your reduction used a HIPE version later then 10.0. This sets which extension of the input FITS files contain the coverage information ("3" for HIPE versions <10.0, "2" after).

CREATE_SUPERSKY_MAP (procedure):

- **Description:** Produces a supersky-subtracted map from the input maps
- **Syntax**: CREATE_SUPERSKY_MAP, FILE1=file1, FILE2=file2, SUPERSKY_FILE=supersky_file, [, /READ_FITS] [, /HIPE10] [, /MOSAIC]
- **Obligatory keywords**:
  - FILE1=file1: name of the 1st input file
  - FILE2=file2: name of the 2nd input file
  - SUPERSKY_FILE=supersky_file: name of the output file (string)
- **Optional keywords**:

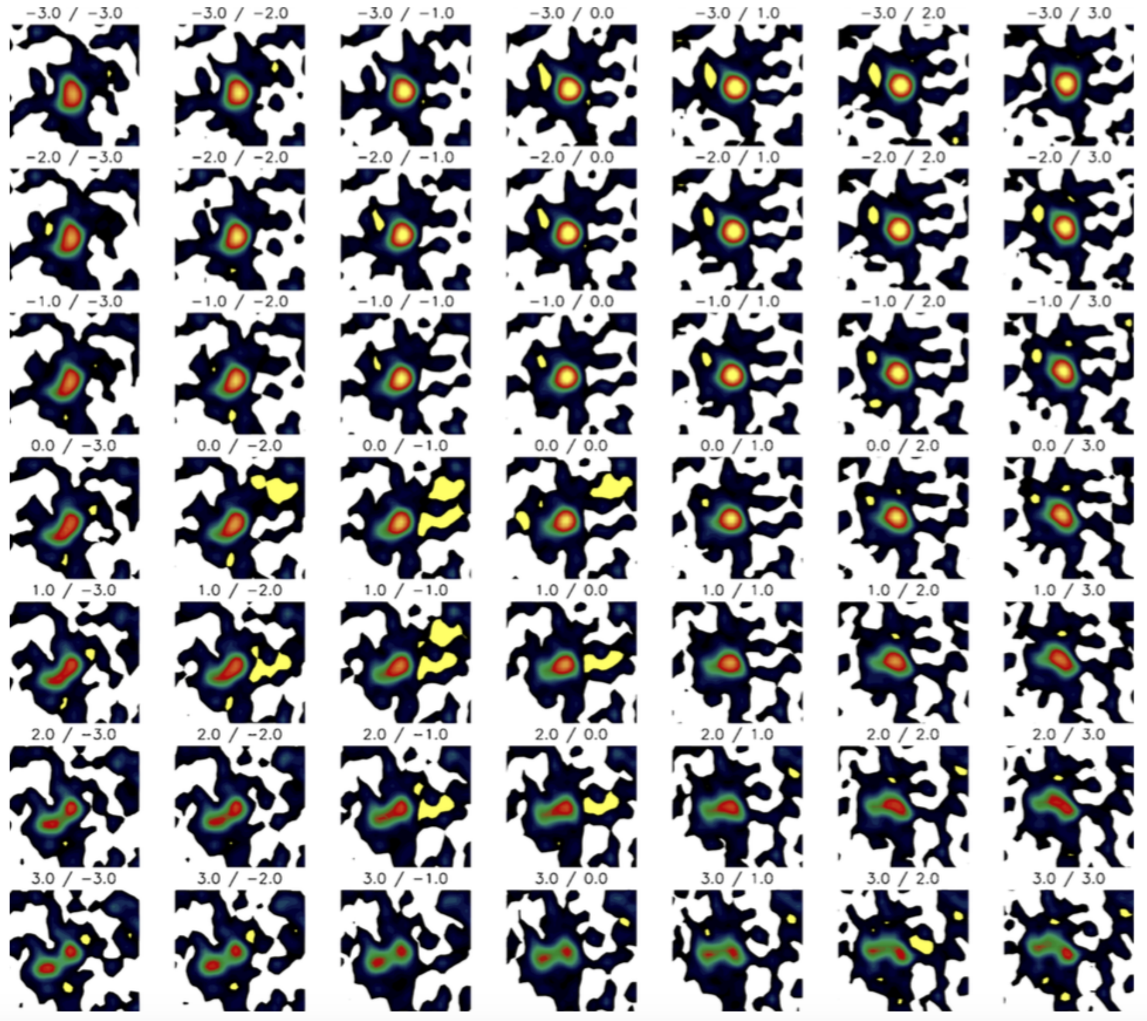

Figure 1: Source matching for Ixion (green band) to determine the optimal offset for the final DDIFF image. Wrong offsets can easily be identified by the distorted or double-peaked shape of the combined image. The numbers above the stamp figures correspond to the actual offsets in arcsec units (the optimal offsets are $-2.0''$ and $+1.0''$ in this case).

- /READ_FITS: set this keyword if the input files are FITS cubes and not FITS files with extensions
- /HIPE10: set this keyword if your reduction used a HIPE version later then 10.0. This sets which extension of the input FITS files contain the coverage information (”3” for HIPE versions <10.0, ”2” after).
- /MOSAIC: set this keyword if the input files were created by the MOSAIC task in HIPE *before* HIPE version 10.0.

CREATE_SHIFTED_MAPS (procedure):

- **Description:** Creates a set of images with shifted coordinate systems (WCS information) from the 2nd visit images of an OTKP data set. The shifted maps are stored in separate folders.

- **Syntax**: CREATE_SHIFTED_MAPS, FILE1=file1, FILE2=file2 [, DIR0=dir0] [, /READ_FITS] [, DRA=dra] [, DDEC=ddec]

- **Obligatory keywords**:

  - FILE1=file1: name of the reference file – this is typically the combined map of the visit-1 images in a specific band
  - FILE2=file2: name of the "shifted" file – coordinate information in this file is changed, and a set of shifted images are created with respect to the coordinate information in FILE1.
  - DIR0=dir0: name of the output directory for the shifted files – there is no default or obligatory value, but the directories are typically named as: <object_name>_<band>_images.

- **Optional keywords**:

  - /READ_FITS: set this switch to if you are using FITS cubes as input files rather than the standard FITS extension setup used by HIPE.
  - DRA=dra: array of coordinate shift values in the R.A. direction in [arcsec] units (1D array, float or double, default: -5...+5″ with 1″ steps)
  - DDEC=ddec: array of coordinate shift values in the DEC direction in [arcsec] units (1D array, float or double, default: -5...+5″ with 1″ steps). Note that the total number of shifted maps is N_RAxN_DEC, where N_RA and N_DEC are the number of elements in the DRA and DDEC variables, respectively.

CREATE_DIFF_MAPS (procedure):

- **Description:** Creates a set of differential images using a reference map and a set of shifted coordinate system maps, created by the CREATE_SHIFTED_MAPS procedure.

- **Syntax**: CREATE_DIFF_MAPS, DIR0=dir0, FILE_VISIT1=file_visit1 [, /READ_FITS] [, /NOCOV] [, DRA=dra] [, DDEC=ddec] [, FLAG=flag]

- **Obligatory keywords**:

  - DIR0=dir0: name of the reference file – this is typically the combined map of the visit-1 images in a specific band
  - FILE_VISIT1=file_visit1: name of the reference (visit-1) image file

- **Optional keywords**:

  - /READ_FITS: set this keyword if you use FITS cubes as input files rather than the standard FITS extension setup used by HIPE. Always set this keyword when you use a set of images created by the CREATE_SHIFTED_MAPS procedure.

- DRA=dra: array of coordinate shift values in the R.A. direction in [arcsec] units (1D array). If not set, it uses the default values (-5...+5 arcsec with 1 arcsec steps) of the CREATE_SHIFTED_MAPS procedure.
- DDEC=ddec: array of coordinate shift values in the DEC direction in [arcsec] units (1D array). It not set, it uses the default values (-5...+5 arcsec with 1 arcsec steps) of the CREATE_SHIFTED_MAPS procedure.
- /NOCOV: ignores coverage information when creating the differential maps
- FLAG=flag: optional additional string in the name of the output files

NOISE_CHECK_RUN (procedure):

- **Description:** Uses a set of differential image to obtain the best coordinate offset between two maps using noise characteristics
- **Syntax**: RESULT = NOISE_CHECK_RUN, DIR0=dir0, FILE_VISIT1=file_visit1 [, /READ_FITS] [, /NOCOV] [, DRA=dra] [, DDEC=ddec] [, FLAG=flag]
- **Output:** RESULT: a two-element array containing the optimal offsets (in pixels) as obtained from the noise characteristics
- **Obligatory keywords**:
  - DIR0=dir0: name of the reference file – this is typically the combined map of the visit-1 images in a specific band
  - FILE_VISIT1=file_visit1: name of the reference (visit-1) image file
- **Optional keywords**:
  - /COVERAGE: if set, the procedure uses pixel in the relative coverage limits set in the LIMITS keyword to obtain noise statistics (by default it uses a small rectangular region around the source)
  - LIMITS=limits: a 2-element array with the minimum and maximum relative coverage value that should be used for noise characterisation
  - /PS: if set, an output EPS file *noise_check_run.eps* is produced containing the noise contour map.
  - DX=dx: range investigated in the "X" image direction (in pixel units, default: -5...+5 pixels)
  - DY=dy: range investigated in the "Y" image direction (in pixel units, default: -5...+5 pixels)

CREATE_DDIFF_MAPS (procedure):

- **Description:** Creates a set of double differential images using the maps created by the CREATE_SHIFTED_MAPS and CREATE_DIFF_MAPS procedures.
- **Syntax**: CREATE_DDIFF_MAPS, FILE1=file1, FILE2=file2, IM_DIFF=im_diff, COV_DIFF=cov_diff, DIR_OUT=DIR_OUT, SHIFT_RA=shift_ra, SHIFT_DEC=shift_dec [, CENTER_1=center_1] [, CENTER_2=center_2]

- **Obligatory keywords**:
  - FILE1=file1: file name of the original visit-1 image
  - FILE2=file2: file name of the original visit-2 image
  - IM_DIFF=im_diff: file name of the differential image
  - COV_DIFF=cov_diff: file name of the image containing the coverage information of the differential image
  - DIR_OUT=dir_out: directory for the output file(s)
  - SHIFT_RA=shift_ra: offset between the two images with respect to the original coordinate systems in the R.A. direction in [arcsec] units
  - SHIFT_DEC=shift_dec: offset between the two images with respect to the original coordinate systems in the DEC direction in [arcsec] units
- **Optional keywords**:
  - CENTER_1=center_1: a two-element array with the R.A. and DEC coordinates of the requested center for the first image as set by FILE1 (if not supplied, the center of the image is assumed)
  - CENTER_2=center_2: a two-element array with the R.A. and DEC coordinates of the requested center for the second image as set by FILE2 (if not supplied, the center of the image is assumed)
  - /READFITS: assumes data cube FITS files instead of FITS files with extensions

PLOT_SHIFTED_CONTOUR_MAPS (procedure):

- **Description:** This function uses a set of double-differential images to find the optimum offset (coordinate shift) between the 1st and 2nd beam of the same target (see the previous subsection for details). The function provides a "stamp map" where the double-differential images obtained with various offset can be visually inspected (distorted PSF, double-looking sources, etc.). It also gives a "hint" for the best set of offsets as a string (as the "result" of the function).
- **Syntax**: RESULT = PLOT_SHIFTED_CONTOUR_MAPS, DIR0=dir0, [, DSIZE=dsize] [, /READ_FITS] [, /SHOW] [, /HALF] [, /BIG] [, CENTER=center]
- **Output:** RESULT: A string containing the hint for the best offset. The procedure also produces an EPS file as output with the stamp map.
- **Obligatory keywords**:
  - DIR0=dir0: the name of the directory containing the double-differential images to be investigated
- **Optional keywords**:
  - DSIZE=dsize: the half-size of the region (square) around the requested coordinate to be mapped (default: 10 arcsec).

- /READFITS: assumes data cube FITS files instead of FITS files with extensions
- /SHOW: displays the generate EPS file using *gv* (ghostview).
- /HALF: uses a find grid with 0.5 arcsec resolution in the -4.5...+4.5 arcsec range instead of the default -4...+4 arcsec range with 1 arcsec resolution.
- /BIG: uses the -6...+6 arcsec range with 1 arcsec resolution instead of the default -4...+4 arcsec range with 1 arcsec resolution.
- CENTER=center: a two-element array with the R.A. and DEC coordinates of the requested center (if not supplied, the center of the image is assumed)

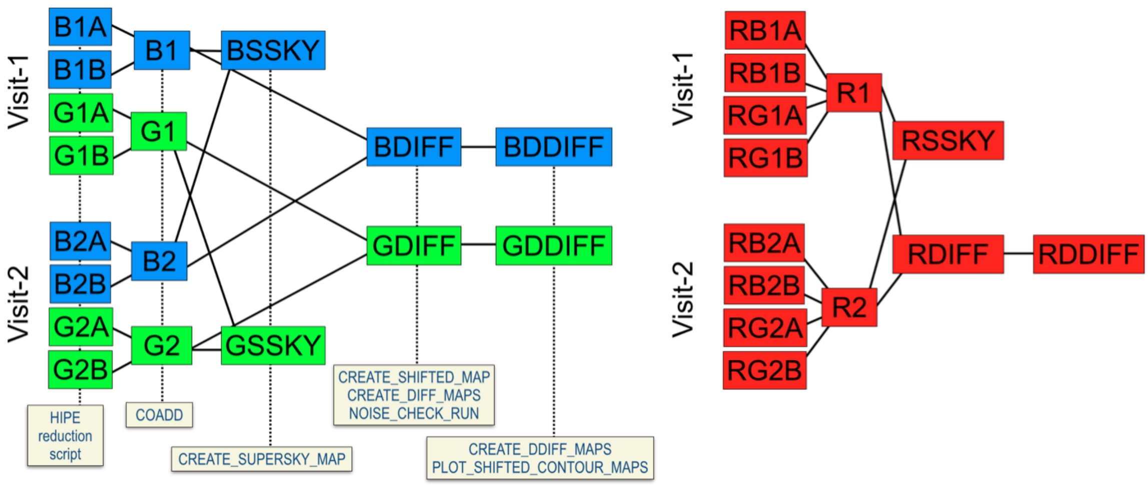

Figure 2: Outline of our standard observing and image derivation scheme for scan map observations of trans-Neptunian objects. The single maps (first column) are combined to obtain the co-added, single visit maps (second column), and these co-added maps are used to produce the different science data products (SSKY, DIFF and DDIFF maps) that are used to obtain the final fluxes. The left and right panels of the figure show the scheme separately for the short wavelength (70/100 μm, or blue/green) and for the long wavelength (160 μm or red) PACS channels. In each box in the first letter marks the filter (B=blue, G=green, R=red), the second marks the epoch (1 = Visit-1, 2 = Visit-2), the third marks the scan direction (A = 70 deg, B = 110 deg). In the case of the red filter sequences the double letters (RB or RG) marks the corresponding short/long wavelength filter combination. The SSKY, DIFF and DDIFF labels correspond to the supersky-subtracted, differential and double-differential images, respectively. The names of the procedures and functions related to specific data combination levels are also shown at the bottom of the figure for the blue PACS photometer detector.

5 Photometry of "TNOs are Cool!" mini scan maps and related image products

5.1 Aperture photometry

Aperture photometry of our targets can be performed using various methods (IDL/DAOPHOT, IRAF, HIPE) on the various image products. However, we have developed our own photometry tool optimised for Herschel/PACS images obtained with our procedures described above ((*PHOT0* and *RUN_PHOT0_TASK* functions, see below). This tool is based on IDL's DAOPHOT procedures. It uses a centroid fitting for the determination of the source's centre position followed by aperture photometry in multiple apertures.

As the default image pixel size is adjusted to the actual FWHM in all PACS bands ($1\farcs1$, $1\farcs4$ and $2\farcs1$ in the blue, green and red bands, respectively), an ideal aperture of 4-5 pixels in radius has been identified in all bands using flux growth curves of several targets. The encircled energy fraction (or aperture correction) coefficients are determined by using a set of measurements of faint calibration stars in all the three PACS bands. Our flux calibration scheme is based on the PACS scan map measurements of HD 139669, γ Dra, HD 170693 and HD 138265.

The absolute photometric accuracy of our full processing scheme – that includes differential, double differential or supersky-subtracted images – cannot be tested entirely using standard star measurements, as these objects do not move with respect to the background, making these types of images meaningless to produce. As the correctness of the flux calibration was approved in the first step (see above), in a second step we used the scan-map measurements of some bright TNOs and Centaurs (Quaoar, Orcus, Ixion and Chariklo, among others) to test whether flux densities are kept during the generation of our combined data products from the differential images to the double differential or supersky-subtracted images. The requirement was that, as the background is negligible for these bright targets, the average flux densities obtained at the original, single visit images must be the same as that of the combined products within the photometric uncertainties. According to these tests the combined data products fulfil this requirement (relative accuracies are better then 5% in all PACS bands).

5.2 Photometric uncertainty

Photometric uncertainty can be determined using the "implanted source" method (*IMPLANTED_SOURCE_NOISE*). In this method we place 200 artificial sources on the image (a single one at a time) and this artificial source has a spatial flux distribution of the PACS point spread function in the actual band. Then the same type of aperture photometry is performed on each implanted source as on the target. The sources are placed in regions with coverage values within a fixed interval (typically $0.25 < \text{coverage} < 0.9$) – this excludes the vicinity of the target as well as the edges of the image where the coverage is low and therefore the noise is high. The photometric uncertainty of the map is taken as the standard deviation of the distribution of the artificial, implanted source fluxes (typically the distribution of these fluxes is very close to Gaussian).

5.3 Tools used for photometry

The interface the user has to work with to perform photometry on the various PACS image products is the *RUN_PHOT0_TASK* function. The PHOT0 function is not an end-user function therefore it is not discussed here in details. Determination of the flux uncertainty of the flux determined with the RUN_PHOT0_TASK function is performed with the *IMPLANTED_SOURCE_NOISE (function)*.

RUN_PHOT0_TASK (function):

- **Description:** Performs aperture photometry on PACS image products
- **Syntax:** RESULT = RUN_PHOT0_TASK(IMAGE=image, BAND=band [, THRESHOLD=threshold] [, DSIZE0=dsize0] [, CENTRE=centre] [, /READ_FITS] [, /EQAT] [, /INVERT] [, FWHM=fwhm] [, /RANDOM_AP], [, SCALE=scale])
- **Output:** RESULT: a N-by-3-element array with the results of the photometry, where N is the number of sources detected and the 3 elements in the 2nd dimension contain the fluxes of the 4 and 5-pixel radius apertures and their average (in [mJy] units)
- **Obligatory keywords:**
  - IMAGE=image: the name of the file to read in (string)
  - BAND=band: the name of the PACS band used [string = 'blue', 'green' or 'red']
- **Optional keywords:**
  - THRESHOLD=thershold: The significance level above which the sources are considered for detection (default: THRESHOLD=3.0)
  - DSIZE=dsize: The size of the box in pixel units in which we look for sources (default: 25 pixels). The area is always considered to be a square.
  - CENTRE=centre: The center of the box in image coordinates in which the algorithm looks for sources (and has a size of *DSIZE*). By default (i.e. when the CENTRE keyword is not supplied), the centre of the image is searched. CENTRE must be a two-element array with CENTRE=[x0,y0] where x0 and y0 are the pixel coordinates of the image centre requested (either integer or floating point type).
  - /READ_FITS: looks for a data cube instead of a FITS file with extensions
  - /EQUAT: returns the fitted equatorial coordinates as well, in addition to the photometry results. In this case RESULT has N-by-5 dimensions instead of N-by-3 (see above), and the R.A. and DEC of the source centers are stored in the [*,3] and [*,4]-th elements (using IDL notation).
  - /INVERT: Performs aperture photometry on the "folded" image (original image times -1; useful for DIFF images).
  - FWHM=fwhm: input parameter for the PHOT0 procedure, the expected approximate FHWM of the sources in pixels (default FWHM=5 in all bands, in agreement with the adjusted 1.1, 1.4 and 2.1 arcsec adjusted pixel sizes.)

- /RANDOM_AP: performs photometry in randomly placed apertures around the source detected for noise determination (obsolte).
- SCALE=scale: pixel scale parameter for the PHOT0 function (default=1.0)

IMPLANTED_SOURCE_NOISE (function):

- **Description:** Calculates the characteristic flux uncertainty for a specific map using the 'implanted source' method, as described above.
- **Syntax**: RESULT = IMPLANTED_SOURCE_NOISE, FB=fb, FCOV=fcov, BAND=band, DIR_PSF=dir_psf, [, COVERAGE_LIMIT=coverage_limit] [, FLUX_SOURCE=flux_source] [, THRESHOLD=threshold] [, GRADIUS=gradius] [, SCALE_0=scale_0] [, /DDIFF] [, DATACUBE=datacube] [, HIPE_MOSAIC=hipe_mosaic] [, MYCOVERAGE=mycoverage]
- **Output:** RESULT: the photometric uncertainty obtained, in [mJy] units
- **Obligatory keywords**:
  - FB=fb: the map on which the determination of the photometric uncertainty is performed
  - FCOV=fcov: coverage map related to the actual image
  - BAND=band: the actual photometric band of the map ('blue', 'green' or 'red')
  - DIR_PSF=dir_psf: the name of the folder where the point spread function FITS images are located
- **Optional keywords**:
  - COVERAGE_LIMIT=coverage_limit: minimum and maximum relative coverage values (i.e. maximum normalized to unity) that are considered in the noise calculation. The default is $0.25 < \text{coverage} < 0.9$.
  - FLUX_SOURCE=flux_source: the total flux of the artificial source implanted to the maps in [Jy] units. The default is 0.3 Jy.
  - THRESHOLD=THRESHOLD: minimum limit of significance used in the artificial (implanted) source flux determination. The default value is 10.
  - GRADIUS=gradius: Size parameter used in the random source implantation (default: 25 pixels)
  - SIZE_0=size_0: scale factor used in the implanted source photometry (default: 1.0)
  - /DDIFF: set this keyword if the photometry is performed on a double-differential (DDIFF) map
  - /DATACUBE: set this keyword if the image and coverage information are stored in the same FITS datacube file (only FB sould be supplied, FCOV not)
  - /HIPE_MOSAIC: set this keyword if the map investigated is a HIPE mosaic image (FCOV may be a separate file)
  - /MYCOVERAGE: set this keyword if the coverage information is stored in a separate file and not covered by other keywords (use FCOV= to locate the file)

6 Light curve targets

Dedicated light curve observations with Herschel/PACS were performed for a few trans-Neptunian objects including Eris, Quaoar, Haumea, Varuna, 2003 AZ84, 2003 VS2, and the Centaur Chiron. Light curve observations are long (typically 4-9 h per visit) and consist of several tens of repetitions of single scan maps using a single scan direction only. Observations at a specific epoch (visit-1) are typically followed by a "follow-on" or "shadow" observation (referred to as visit-2) that allows us to perform background subtraction. In many cases, similar to the "TNOs are Cool!" standard scan map strategy, the visit-2 observation also contains that target at a location different from the one in visit-1. In this case the visit-1 and visit-2 measurements serve as mutual backgrounds, the same way as in the standard cases discussed above.

The need to detect light curve variations and the fact that the source moves notably with respect to the background during a full light curve observation cycle make it necessary to divide the measurements into smaller block that are reduced as individual measurements. In the repetition selection both the starting repetitions (sr=) and the length of the individual blocks (nm=) can be selected, as it is demonstrated in the light curve script attached to this delivery report (see the block starting at line 279 in the attached Jython script *process_lc_example.py*). Table 3 shows a summary table of our lightcurve targets togehter with the expected flux levels, the observed (visual) lightcurve amplitude, as well as an estimated best number of repetitions for the data reduction.

Number/	Name	Approx. flux level [mJy] at 70 μm	at 100 μm	at 160 μm	P_{sid} [hours]	Δmag in V-band	Rep. for LC	Remarks
2 060	Chiron	70	46	24	5.9	0.1	1- 6	
20 000	Varuna	8	13	10	6.3	0.4	5-10	
50 000	Quaoar	32	41	30	8.8-18.8	0.1-0.3	1- 4	binary
84 922	(2003 VS2)	18	16	10	3.7-7.4	0.2	4-10	
134 340	Pluto	280	370	340	153.3	0.3	1	multiple system
136 108	Haumea	17	23	22	2.0-3.9	0.3	2- 5	multiple system
136 199	Eris	2	4	5	3.6-28.1	0.1	10-15	binary
208 996	(2003 AZ_{84})	28	25	17	6.7-13.6	0.1	2- 5	binary

Figure 3: Light curve targets: flux levels in each band, rotation period, visual amplitude, combination of n map repetitions for an individual thermal lightcurve data point with suffcient signal-to-noise ratio (smaller number is refering to the shorter wavelength channels where the target is usually brighter, larger number for the red channel).

In addition, the start and end times of the specific observation blocks are also determined which is essential in the case of light curve data. This is obtained using the *getRepetition-FineTimes.py* script in HIPE. This script uses the basic information extracted during the standard processing or separately with the *lc_base_framesave_hipe13.py* script.

In the case of light curve data photometry, in one hand, can be performed on the original, Level-2 selected repetition block maps produced by our HIPE reduction script. We note again that in these cases no "cross-scan" measurements are available, i.e. the combined (COADD) maps that corresponds to Level-2.5 in the PACS data reduction scheme cannot be produced. Differential (DIFF) and supersky-subtracted (SSKY) maps can also be produced by the same CREATE_DIFF_MAPS and CREATE_SSKY_MAPS algorithms as the same kind of maps of the standard mini scan maps. Photometry and photometric uncertainty determination are also performed by the same methods (RUN_PHOT0_TASK and IMPLANTED_SOURCE_NOISE).

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Appendix

List of related HIPE (jython) scripts

- – main (standard) HIPE reduction script used to process data from Level-0 to Level-2.
- **process_lc_example.py** – sample script for light curve data reduction
- **lc_base_framesave_hipe13.py** – script to extract some basic information from the Herschel Science Archive for a specific OBSID.
- **getRepetitionFineTimes.py** – extracts FINETIME information from the HIPE internal save files (generated by the lc_base_framesave_hipe13.py script)

List of related IDL scripts

- **coadd.pro** (COADD procedure) – co-adds maps (Level-2) based on WCS information
- **create_shifted_maps.pro** (CREATE_SHIFTED_MAPS procedure) – creates intermediate step shifted maps from coadded scan maps
- **create_diff_maps.pro** (CREATE_DIFF_MAPS procedure) – creates differential maps from Level-2 maps

- **noise_check_run.pro** (NOISE_CHECK_RUN procedure) – determines the optimal offset between the two coordinate systems of two maps
- **create_ddiff_maps.pro** (CREATE_DDIFF_MAPS procudure) – creates double-differential maps from differential maps
- **create_supersky_map.pro** (CREATE_SUPERSKY_MAP procedure) – creates supersky-subtracted maps from Level-2 or Level-2.5 (co-added) maps
- **plot_shifted_contour_maps.pro** (PLOT_SHIFTED_CONTOUR_MAP procedure)
- **PHOT0.pro** (PHOT0 function) – Herschel/PACS point source photometry core function
- **run_phot0_task.pro** (RUN_PHOT0_TASK function) – end-user function for point source photometry on Herschel/PACS maps
- **implanted_source_noise.pro** (IMPLANTED_SOURCE_NOISE function) – photometric uncertainty determination of Herschel/PACS maps

Auxiliary files

- PACS point spread function images used by the implanted source method for photometric uncertainty determination (used by the IMPLANTED_SOURCE_NOISE function):
  - **combined_psf_blue_1.10.fits** ("blue" band, 70 μm)
  - **combined_psf_green_1.40.fits** ("green" band, 100 μm)
  - **combined_psf_red_2.10.fits** ("red" band, 160 μm)