esac

European Space Astronomy Centre (ESAC)
P.O. Box, 78
28691 Villanueva de la Cañada, Madrid
Spain

DOCUMENT

Dealing with Semi-Extended Sources Observed with PACS Spectroscopy

Prepared by	**Katrina Exter**
Reference	**HERSCHEL-HSC-DOC-2313**
Issue	**1**
Revision	**0**
Date of Issue	**01/03/2018**
Status	**For release**
Document Type	**User Note**
Distribution	**HSC, SAT**

CHANGE LOG

Reason for change	Draft Issue	Revision	Date
First version of document	1	0	01/03/2018

Table of Contents

1 INTRODUCTION

This user note is to explain how to work with semi-extended sources with PACS spectroscopy.

Semi-extended sources are those sources with a full extent no larger than 30″ and which are located in the central region of a re-binned cube (a single PACS spectroscopy pointing). For such sources it is possible to perform a "semi-extended source" correction to the spectrum extracted from the central region of the cube, to produce a result that is superior to simply extracting the summed spectrum of the spaxels covering the source. The reason for this is that aperture extractions from a cube do not correct fully for the flux "falling between" spaxels. These gaps are a consequence of the uneven illumination of the PACS FoV. This is corrected for by the PACS flux calibration only for fully extended sources: any other source morphology will require extra flux corrections. More detail on the uneven illumination can be found in the PACS Handbook and the user note on working with extended sources. In addition, and especially for the smaller semi-extended sources (those not much larger than a point), the semi-extended correction will also adjust for the flux falling outside of the spaxel(s) where the target is visible (because the beam is larger than a spaxel, in fact its wings even extend slightly beyond the 47″x47″ FoV of a re-binned cube).

The semi-extended source corrections do not require a reprocessing of the data, as the starting point are the re-binned cubes taken from Level 2 or 2.5 of an observation. However, it is necessary to use HIPE to apply the correction tasks. It is also necessary to have a model of the source: it shape, size, and location.

Before reading this user note you should be familiar with PACS spectroscopy, in particular with the various observing modes that were used and different types of cubes that were produced. These are explained in the Quick-Start Guide, and in more detail in the PACS Products Explained and the PACS Handbook, all of which can be found in the Herschel Explanatory Legacy Library (HELL: PACS section). To follow the advice given in this release note, the user should have at least read the Quick-Start Guide. Definitions are provided at the end of this release note, but to *understand* the terms defined, it is necessary to read the other documentation. Additionally, the tasks discussed in this note are explained, and their parameters defined, in the Help documentation available from HIPE, in particular the PACS Data Reduction Guide (spectroscopy) and the Users Reference Manual.

2 PRE-REQUISITES

The first pre-requisite is that the user knows the surface brightness distribution of their source at the PACS wavelengths, i.e. must be able to model its morphology in the observed field. This model must represent what the source *is* at the wavelength of the observation, not only what it looks like when seen with PACS – in other words, the model must not be the source convolved with a beam, but the source alone. This is something that *cannot* be determined from the PACS data alone (neither photometry nor spectroscopy) as the spatial resolution is not good enough to adequately map 30″-sized targets. The information that has to be provided for this model is the shape of the source (e.g. Gaussian, circular, Top Hat), its dimensions, position angle (if relevant), and its coordinates on the sky (or more specifically, its offset from the centre of the field). If you have a high-resolution image with a WCS then this can be used instead of a model, as long as it shows your source only. For this to work, the spatial resolution of the image must not be dominated by the PSF of the instrument that took the image.

The second pre-requisite is that the user knows the observing mode. This is important when discussing which products to use, what issues to be aware of, and the calibration uncertainties. This information can be gotten from various sources: the FITS header keywords of the final-level cubes in an observation, a spreadsheet containing these keywords for all observations, and the PACS Observation Summary which is provided in all observations (but can only be read in HIPE; although it may soon also be provided on the HSA search results page). How to find these information is explained in the PACS Products Explained.

The third is that the user knows how to open a cube in HIPE, and they are willing to work in HIPE to apply the corrections. The Spectrum Explorer is especially useful for inspecting and extracting spectral or spatial regions from cubes. For the type of cube that are necessary to use in these semi-extended source corrections, it provides capabilities that are very difficult to find outside of HIPE.

Finally, it is necessary that spectrum of the source is not contaminated by another source (e.g. a background or an adjacent source). The corrections used for semi-extended sources are multiplicative, and they are only fully applicable if the observed spectrum is from the modelled source alone. If your source is blended with another source, your choices are to either accept the additional uncertainty (which you will also have to calculate yourself, as it is highly dependent on the nature of the blended emission), or to remove the contamination, e.g. subtract it out before applying the corrections to the cubes. See Appendix 1 to learn about removing contamination.

A comment about pointed vs. mapping observations. The corrections discussed in this user note are applied to the re-binned cubes, which are provided for all observations and are the main science end-product for pointed observations. It was always assumed that observers of small sources would use the pointed observing mode, and this assumption is found in this user note also. The tasks discussed here will also work on mapping observations, as long as they are applied to the re-binned cubes, not the mosaic cubes.

3 HOW DOES THE "E2P" CORRECTION WORK?

The "E2P" correction – extended-to-point source correction – is explained in a technical note, a script, and a set of slides from a tutorial, and these can be found in HELL PACS section Level 2 (under *Data Processing*: "PACS Spectrometer Semi-extended sources"). The technical note explains how the corrections work, the slides give examples of its results, and the scripts show how to perform the corrections. The starting point is a slicedRebinnedCubes taken from Level 2.5 for un-chopped range scan observations and Level 2 for all others. The point-source correction task extractCentralSpectrum is run on these cubes, outputting three spectra: c1, c9, and c129. These spectra are explained in the user note on point sources, which also located in the PACS HELL Level 2; for the E2P corrections it is generally recommended to use c9 if your source is offset from the centre, and c129 otherwise. The next step is to define the model or locate the image you want to use instead. Then the task specExtendedToPointCorrection is run, with the spectrum and the model or image as inputs. Finally, the c9 or c129 spectrum is divided (with the task divide) by the output of specExtendedToPointCorrection, to create the corrected semi-extended source spectrum.

The default model of specExtendedToPointCorrection is a Top Hat. The slides provided in HELL include a model of a Gaussian, and this model is also demonstrated in the user note on point sources. The code for using an image input is included in the slides mentioned above.

4 UNCERTAINTIES

The E2P tasks were written to be used on semi-extended sources that are located in and around the central spaxel. The two tasks that compute corrections in this process are extractCentralSpectrum and specExtendedToPointCorrection, both of which depend on a model of the PACS beam. The beam used in the computation of the corrections that are used by extractCentralSpectrum is that of the central spaxel only, so for sources located in another spaxel, its output spectrum (c9 or c129) will have a slightly incorrect calibration applied (this is explained in the user note on point sources). The beams used in correction calculated by specExtendedToPointCorrection are those of the central 3x3 spaxels and so the source can be located within this area and have a good E2P calibration.

The dominant source of uncertainty in the E2P correction is likely to be that of the input model or the input image. There are two ways in which an incorrect model can result in a bad correction:

- The uneven illumination of the PACS IFU is due to the fact that the beams of the individual spaxels are not perfect. They do not create a grid of 9.4″ contiguous spaxels, but rather can be better described as a grid of 8″ spaxels with gaps between. The E2P flux correction depends on *where* the source/model lies in the FoV, since the pattern of these "gaps" varies over the plane of the IFU (an image of this pattern can be found in the user note on extended sources). So the same model in different locations will have slightly different corrections.
- An incorrect model will result in a wrong ratio of the surface brightness of the source to that of a point source, and hence a wrong E2P calibration.

What uncertainties arise from *not* applying the E2P correction? Clearly this depends on how large the correction would be for your source. Some E2P correction curves (that is, the correction to apply to c9 or c129) computed for an elliptical Top Hat and a Gaussian model are shown in the slides provided on HELL, and these can be consulted to see how significant the correction is for various source sizes: the correction values shown in these figures range from almost 1 to almost 0.1.

If you have a mapping observation of your source, an obvious question is: is the E2P correction necessary, can I not simply sum up the flux of my source from one of the mosaic cubes? How good a result this will produce clearly depends on the shape of the source, its location in the field, and the pointing pattern of the observation. The E2P task corrects for the uneven illumination of the FoV and for the size of the beam (i.e. that the beam is larger than most semi-extended sources). Mapping observations will act to fill in the gaps, but none of the standard mapping patterns used by PACS observers could do this perfectly. If you can even guess at the source shape, or have a high-resolution image that is even roughly correct, we suggest you run the E2P task and compare the resulting spectrum to that extracted directly from the mosaic cube, to see how different they are.

For those who wish to study more deeply the difference between summing the flux in a mosaic cube and using the E2P correction, a more thorough testing can be done with the E2P tasks run on cubes of simulated data. Creating simulated cubes is explained in the user note on point sources. The steps would be to (i) create a set of re-binned cubes with simulated data and using your mapping observation as a guide to how many cubes (how many raster positions) to create and how to modify the model offset value you need to record for each cube, (ii) join the re-binned cubes together into a PacsSlicedRebinnedCube and read that into one of the mosaic tasks – specProject or specInterpolate – to create a simulated mosaic cube, (iii) and then compare the spectrum taken from that to the spectrum computed by the E2P tasks performed on one of the simulated re-binned cubes.

One final word on the uncertainties. For un-chopped observations, the continuum uncertainty for each spaxel of a re-binned cube is ±20 Jy. The uncertainty in the sum of several spaxels (e.g. c9 and the output of the E2P tasks) is therefore the added uncertainty for all the spaxels that were summed up, and will therefore be very high indeed.

Appendix 1 How to remove contamination

If your point source is contaminated by another source of emission – most likely a background – this should be removed this before running extractCentralSpectrum and the subsequent E2P tasks. Since this task works on re-binned cubes, it is on these that you need to work. To subtract out the contamination you can fit and subtract it with the Spectrum Toolbox of the Spectrum Explorer. This toolbox is explained in the HIPE help documentation (the Data Analysis Guide): the steps are to find the nicest-looking spectrum in the cube, fit the contamination of that spectrum, and then use the "MultiFit" part of the toobox to extend that fitting to the entire cube. The output of the fitting is a set of cubes: one cube per model (e.g. the continuum fit), one total model, and the residual (data – model). In your case, the residual is then the point source with the contamination removed.

However, you cannot use the residual cube directly in the E2P or point source tasks. The reason is that the class of output that the fitter creates is a SpectralSimpleCube, and this is not the correct class of cube for extractCentralSpectrum to work on (the task requires a PacsRe-binnedCube). The work-around is the to copy the image array from the residual cube to the re-binned cube you fit:

```
obsid = 1342....
obs=getObservation(obsid,useHsa=1)
# Grab the blue slicedRebinnedCubes from Level 2
slicedRebinnedCubes = obs.refs["level2"].product.refs["HPS3DRB"].product
# For you: a security copy, as slicedRebinnedCubes itself is changed below
slicedRebinnedCubes_cp = slicedRebinnedCubes.copy()
# Get the first cube in slicedRebinnedCubes
cube = slicedRebinnedCubes.get(0)
# Open the Spectrum Explorer and from there the Spectrum Toolbox. Do your fitting
# The outputs from the multifitting in there are, for a single model
# (polynominal) fit, are:
"""
HIPE> # Added variable: FitResult
HIPE> # Added variable: SFGResultsContext
HIPE> # Added variable: MultiFit_Residual
HIPE> # Added variable: MultiFit_TotModel
HIPE> # Added variable: MultiFit_Parms
HIPE> # Added variable: MultiFit_ParameterCube
HIPE> # Added variable: MultiFit_M1
"""
# Get the "image" array from the residual - the fluxes
image = MultiFit_Residual["image"].data
# Replace the fluxes in cube with those from MultiFit_Residual
cube.setImage(image)
# Then push cube back into slicedRebinnedCubes – slice 0 (and then 1, 2…)
slicedRebinnedCubes.replace(0,cube)

# Repeat for however many cubes in slicedRebinnedCubes you want to work with
```

Appendix 2 Glossary

Chop-Nod observing mode: Two ways were provided by PACS to sample the background from an off position. These are explained in the PACS Handbook. The chop-nod mode was the most used because it produced data with a better continuum reliability and slightly better SNR. In this mode the telescope chopped between an on-source and off-source location at two nod positions.

FoV: field of view

HELL: Herschel Explanatory Legacy Library, to be found from the ESA-Herschel site

HSA: Herschel Science Archive

HIPE: Herschel Interactive Processing Environment

Mapping observing mode: Two pointing modes were offered for observing with PACS. Mapping observations were performed as a raster of pointings.

Mosaic cubes (Interpolated, Projected, Drizzled): Mosaic cubes are those created by combining individual cubes taken in a mapping observation: separate and slightly-offset pointings combined to observe either a larger field or to improve the spatial sampling of the source.

Pointed observing mode: Pointed mode observations were on a single FoV, and the primary science products are re-binned or interpolated cube, and point-source tables.

Re-binned cubes: "Re-binned cubes" are the final fully-calibrated native cubes that are produced by the pipeline: one cube per requested wavelength range and, for mapping observations, per raster position. It is from the re-binned cubes that the mosaic cubes are produced – these mosaic cubes being the end product for most mapping observations and one possible end product for pointed observations. (The re-binned cubes have the 5x5 grid of 9.4″-sized spaxels that is the native sky footprint of the PACS IFU, while the spatial grid of the mosaic cubes depends on the mapping field requested by the observer and the size chosen for the mosaicked spatial pixels.)

SPG: Standard Product Generator, short-hand for the automatic pipeline run at the HSC for all Herschel observations. The SPG download/products are the "pipeline" products that a user downloads from the HSA after an archive search.

Spatial Pixel/Spaxel: Both are the name given to the pixels of a cube, each of which contains a full spectrum for a small patch of sky. The difference is that *spaxel* usually refers to the pixel of a native cube (for PACS that is the re-binned cube) with an area that is determined only by the instrument (i.e. 9.4″ for PACS); *spatial pixel* refers to the pixel of a mosaic cube, and it can have any size – the ideal size depends on the mosaicking algorithm and the pointing pattern of the observation (how many overlapping spaxels are there in each spatial pixel?).

Un-chopped observing mode: Two ways were provided by PACS to sample the background from an off position. These are explained in the PACS Handbook. The Un-chopped mode was offered for observations of crowded sources where the off-position had to be especially chosen. A block of on-source was followed by a block of off-source observing