Herschel Spectrometers Workshop
PACS Spectrometer Session #3

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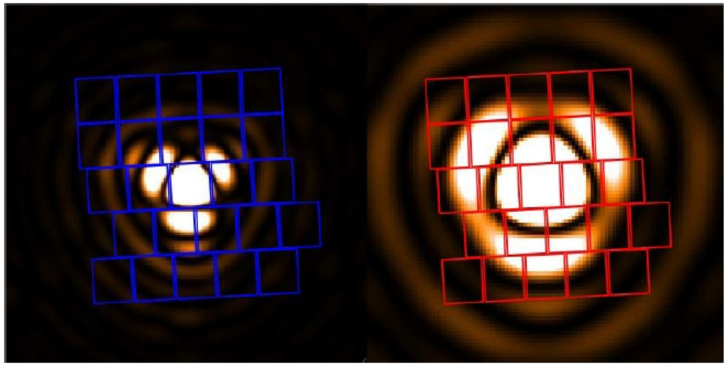
Outline

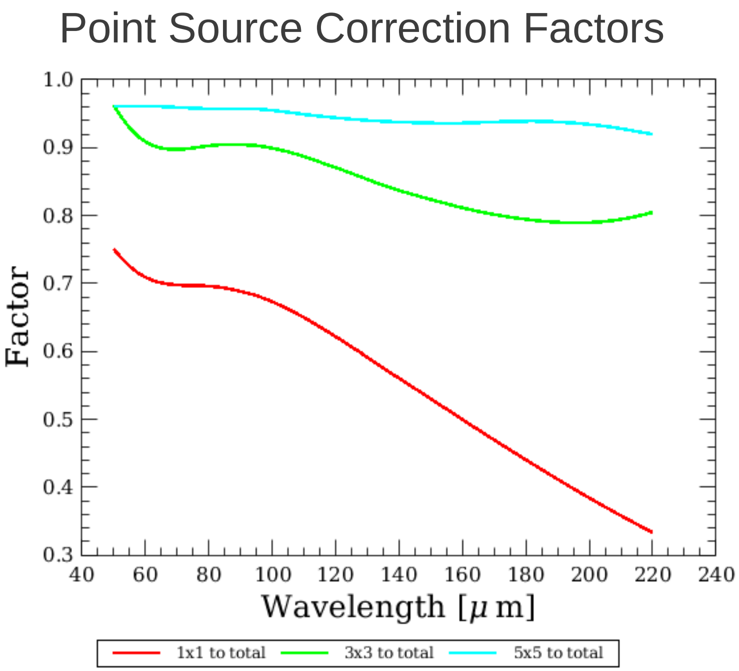
- Session #3: Semi-extended Source Spectra:
  1. Flux Correction for slightly extended objects
  2. Combination of PACS spectra with PACS photometry
  3. Sources comparable to the PACS FOV: using the 5x5
  4. How to use the beam information to simulate PACS observations

PACS Extended and Point Source Calibration

- Extended source calibrated data: Level 2 RebinnedCube/projectedCube. As flatfield is calculated using telescope background in Chop off position (extended emission) Surface brightness [Jy/spaxel]

- Point source calibrated data: post-processing steps to correct from beam truncation, given finite physical detector size (extractCentralSpectrum task) flux density [Jy]
  - C1: central spaxel + PSC (central/total)
  - C9: 3x3 central spaxels + PSC (3x3/total)
  - C129: central spaxel scaled to C9





Semi-extended Sources

Semi-extended correction applied to point-source calibration scheme

Point-Source Calibration
$$F_{point}[Jy]=I_{ext}\left[\frac{Jy}{spaxel};\frac{MJy}{sr};\frac{W}{Hz.m^2.sr}\right].C_{point}$$

C_{point} :point-Source conversion factor

Semi-extended source
$$F_s=I_{ext}.C_s=I_{ext}.C_{point}.\frac{C_s}{C_{point}}=I_{ext}.C_{point}.\frac{1}{C_{cen\lambda}}$$

Source spatial brightness distribution

$$\Omega_{source}(\nu)=\iint_{2\pi} D_\nu(\Psi)\,d\Psi$$

Beam profile

$$\Omega_{beam}(\nu)=\iint_{2\pi} P_\nu(\Psi)\,d\Psi$$

Coupling efficiency

$$\eta_f(\nu,\Omega_{source})=\frac{\iint_{2\pi} P_\nu(\Psi-\Omega_0)D_\nu(\Psi)\,d\Psi}{\iint_{2\pi} P_\nu(\Psi)\,d\Psi}$$

$$\frac{C_s}{C_{point}}=\eta_c(\nu,\Omega_{source}).\frac{\Omega_{source}}{\eta_f(\nu,\Omega_{source})\Omega_{beam}(\nu)}$$

$$\frac{C_s}{C_{point}}=\eta_c(\nu,\Omega_{source}).\frac{\iint_{2\pi} P_\nu(\Psi)\delta_\nu(\Psi)\,d\Psi}{\iint_{2\pi} P_\nu(\Psi-\Omega_0)D_\nu(\Psi)\,d\Psi}.\iint_{2\pi} D_\nu(\Psi)\,d\Psi$$

What is calculated for PACS....

$$C_{cen\lambda}=\frac{C_{point}}{C_s}=\frac{F_{22\lambda\,ext}}{F_{22\lambda\,point}}=\frac{\sum_{i,j} B_{22\,ij\lambda}.\frac{S_{ij}^{ext}}{\sum_{i,j} S_{ij}^{ext}}}{\sum_{i,j} B_{22\,ij\lambda}.\frac{S_{ij}^{point}}{\sum_{i,j} S_{ij}^{point}}}\equiv\frac{\frac{\iint_{i,j} P_\nu(\Psi-\Omega_0)D_\nu(\Psi)\,d\Psi}{\iint_{i,j} D_\nu(\Psi)\,d\Psi}}{\frac{\iint_{i,j} P_\nu(\Psi-\Omega_0)\delta(\Psi)\,d\Psi}{\iint_{i,j}\delta(\Psi)\,d\Psi}}=\frac{\iint_{i,j} P_\nu(\Psi-\Omega_0)D_\nu(\Psi)\,d\Psi}{\iint_{i,j} P_\nu(\Psi-\Omega_0)\delta(\Psi)\,d\Psi.\iint_{i,j} D_\nu(\Psi)\,d\Psi}$$

Semi-extended Source Spectra

- Correction to account for the the coupling of the source distribution model with the PACS beam profiles
- Requires:
  - model of the source's brightness distribution
  - knowledge of the beam efficiencies
- Assumptions:
  - Chosen model is representative of source's distribution
  - source model is valid at all wavelengths per band
- In HIPE: task pacsExtendedToPointCorrection (E2P hereafter), but in HIPE 12.0 it is not used in any ipipe script.

  Documentation: PACS Data Reduction Guide Spectroscopy Sect. 7.8 and the URM (User Reference Manual) for the task.

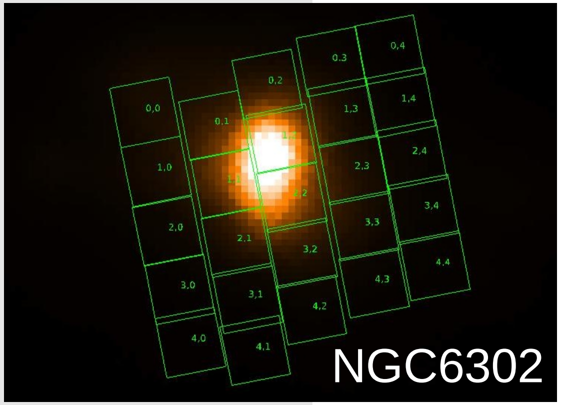
Source Flux Distribution Model

- Ellipse top-hat function (default for the task)

```
e2pCorr1 = specExtendedToPointCorrection(spectrum,calTree=calTree,srcRadX=diam/2.,srcRadY=diam/2.,
           srcAngle=0.0,raOffset=0.0,decOffset=0.0,central3x3=False,extra=True)
```

- User defined analytical model (e.g. Gaussian function)
  - Requires some programming and the class must have a method named getFlux

```
from herschel.pacs.spg.spec.beams import ExtendedSource
from math import *
class MySource(ExtendedSource):
    sigma = 0.0
    offRa = 0.0
    offDec = 0.0
    def __init__(self,diameter, offRa, offDec):
        self.sigma = diameter/2.3548
        self.offRa = offRa
        self.offDec = offDec
    def getFlux(self,relRa,relDec):
        flux = exp(-(0.5*((relRa-self.offRa)/self.sigma)**2+0.5*((relDec-self.offDec)/self.sigma)**2))
        return flux
# Gaussian source with 5.0 arcsec diameter
 source = MySource(5.0)
 e2pCorr = specExtendedToPointCorrection(spectrum,calTree=calTree,userSource=source, central3x3=False)
```



  - Sources well represented by Gaussian are convenient, as and estimate of their spatial extent can be derived from PACS photometer maps and Neptune photometer maps, assuming a Gaussian PSF
- Offsets from perfect centre of central spaxel

$$\sigma_{extent} = \sqrt{(\sigma_{source}^2 - \sigma_{Neptune}^2)}$$

Source Flux Distribution Model

- Directly provide high resolution image of the source (not dominated by PSF)

```
from herschel.pacs.spg.spec.beams import ImageExtendedSource
image = fitsReader(file = '/directory/myMap.fits')
extsrc = ImageExtendedSource(image,ra_source,dec_source)
e2pCorr1 = specExtendedToPointCorrection(spectrum,calTree=calTree,userSource=extsrc,central3x3=False, extra=True)
```

- The adequacy of the model determines the largest uncertainty of this correction

PACS Beam efficiencies

- Calculated beam efficiencies are available at the PACS calibration page (.fits files) and as part ot the PACS calibration Tree
- Calculated based on Neptune raster maps at a few selected wavelengths
- Luckily, specExtendedToPointCorrection in HIPE handles directly the beams, but we will extend on the PACS beams in Sect. 4 of this presentation

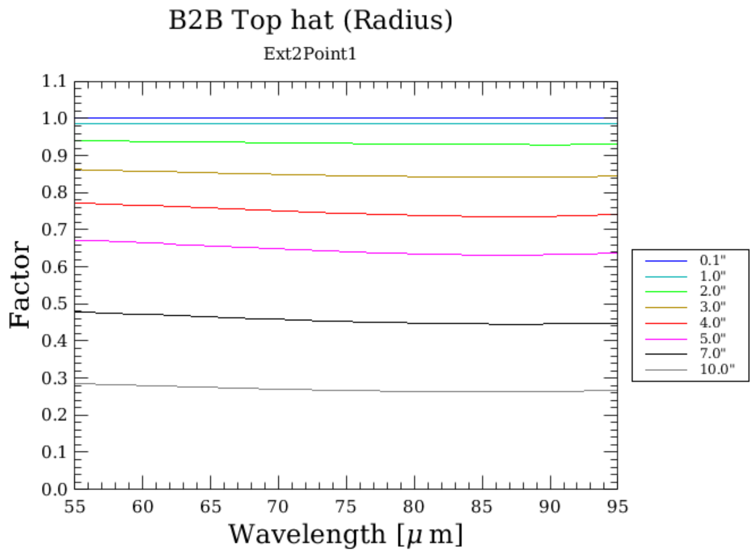
PACS spectrometer calibration

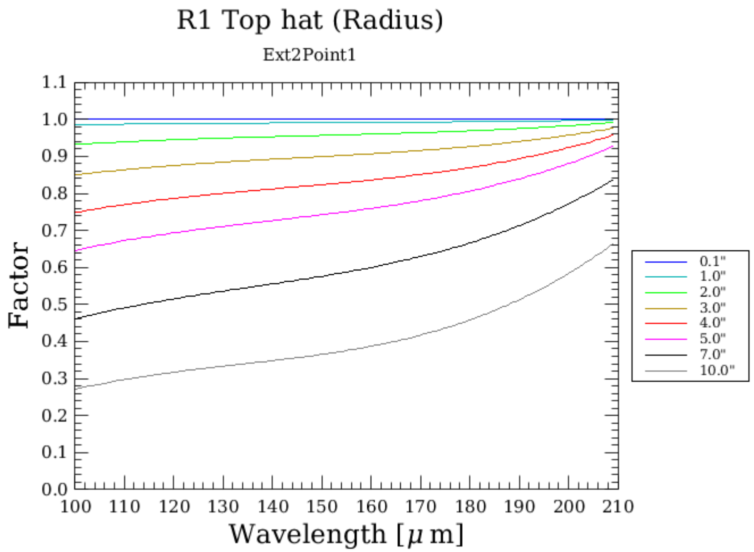
- **PACS Spectrometer performance and calibration**: The PACS Spectrometer Calibration Document v2.4 (16-June-2011) provides details on the calibration accuracy and the necessary information to optimally interpret PACS spectroscopy observations. (Please note, this document refers to the calibration status and performance of pipeline version v8.0. An update compatible with HIPE v12.0 release will be provided soon.) This includes:
  - flux calibration accuracies for chop nod and unchopped observations
  - the beam efficiencies and the PACS integral field footprint
  - spectral leakages and ghosts
  - wavelength calibration, including information on a skew our native line profile develops as a point source moves off the centre of a spaxel
  - table of the point source correction factors for different wavelengths
- The calibration of the spectrometer is based on repeated measurements of planets, asteroids, and stars. The RMS scatter of these measurements are just over 10% within any spectral band, about the same when comparing different spaxels, and similar (but higher in the red) when looking for broad-band features within any band. These calibration certainties are independent, and should be combined when quoting errors in science papers. Read the above-mentioned document for the most up-to-date information.

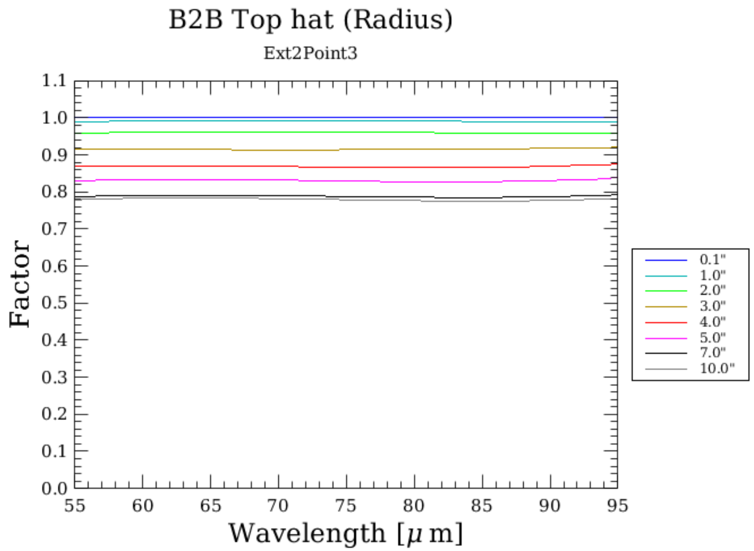
- **PACS spectrometer beams**, version 3, can be downloaded here: PCalSpectrometer_Beam_v3.tar.gz. These beams are based on measurements of a raster with step size 2.5" around Neptune. These beams are useful to compare the flux seen in the different IFU spaxels with with a point source, or a certain brightness distribution in the sky. Version 3 has the beam effiencies for all IFU spaxels, and has a drastic improvement wrt version 2 since the spacecraft pointing was reconstructed more accurately. This resulted in a non-equidistant sampling of the beam efficiency in the sky. The beam products offered are equidistantly sampled on a grid of 0.5 arcseconds. The central part of the beam is the Gaussian fit to the measured beam efficiencies. This has been verified to be a very good description on the different raster observations we have of the central spaxels for wavelengths longer than 80 micron. Below 80 micron, the actual beam shows the square detector footprint, and the Gaussian approximation in the beam products v3 overpredicts the real beam efficiency by 1.5 to 2 percent. The outer part of the beams contains the interpolated values of the irregularly sampled measurements. Thanks to the improved data reduction quality, version 3 of the spectrometer beams are sharper than version 2, and shows the ghosts (see also the PACS spectrometer calibration document) more clearly, as well as the three-lobe structure of the Herschel telescope PSF. Each beam is normalised to the fitted peak value of the central spaxel. The WCS associated with the beam is in sky coordinates for position angle 0.
- The **raw data** from which the PACS spectrometer beams above have been derived, is also made available to the users in tables (y, z offset - signal):
  - SpecSpatial_BeamEfficiency_central_spaxel_tables_v1.tar.gz: Raw measurements PACS beams - central spaxel only. This contains a fits file for each wavelength measured for the CENTRAL SPAXEL only. Raw data of the coarse and fine rasters are combined. The array dimension of the fits file is [3,npoints] where the first column gives the y raster position, the 2nd column the z raster position and the 3rd column the normalised flux measured at this raster position.
  - SpecSpatial_BeamEfficiency_tables_v1.tar.gz: Raw measurements PACS beams - all spaxels, coarse raster measurements only: each fits files corresponds to one wavelength. Each file contains the data for all spaxels of the coarse raster measurement only. Each fits file holds an array of 3x25x25x25 where: (0,25,25,25)=y raster position, (1,25,25,25)=z raster position, (2,25,25,25)=flux normalized to the central spaxel. The second and third dimensions are the raster position indices (y and z) and the last dimension is the module number (=spaxel number).

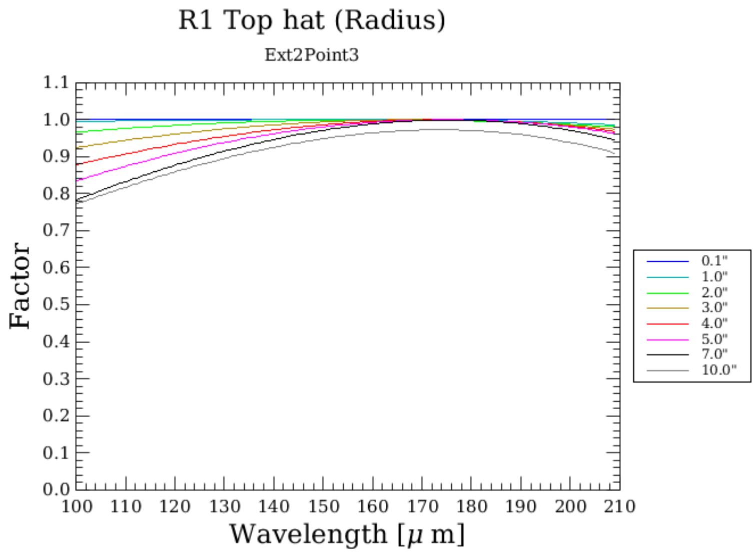
- **Point source observations**. We provide a task at the end of the pipeline scripts to extract the spectrum of point sources, corrected for flux losses due to the PSF being larger than the spaxel size, and including a correction for flux losses due to small pointing offsets from the centre of the the central spaxel and pointing jitter. This task (extractCentralSpectrum) is used on cubes of a single pointing (i.e. not those created from combine several raster pointings) and *must* be run in order to correctly extract the spectrum of point sources. This task uses the beams we refer to above. The pros and cons and how and when to use the task are documented in the spectrometer PDRG (in the pipeline chapters and again in chap. 7).

E2P Corrections: Elliptical Top-hat

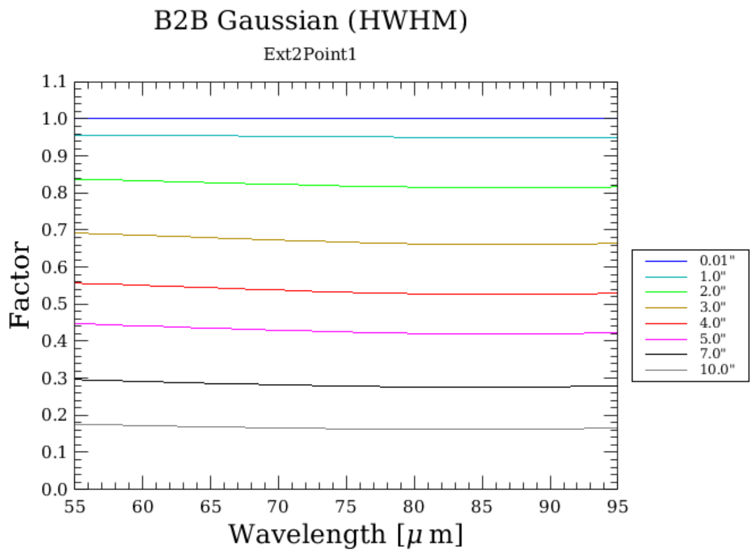


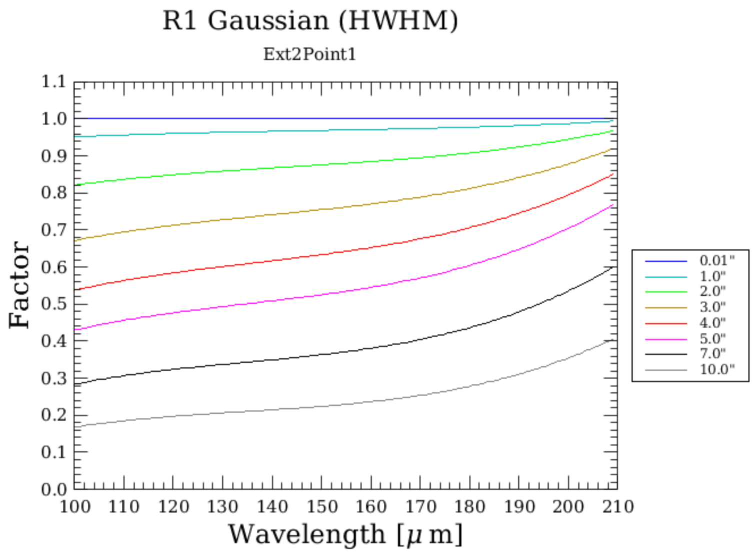


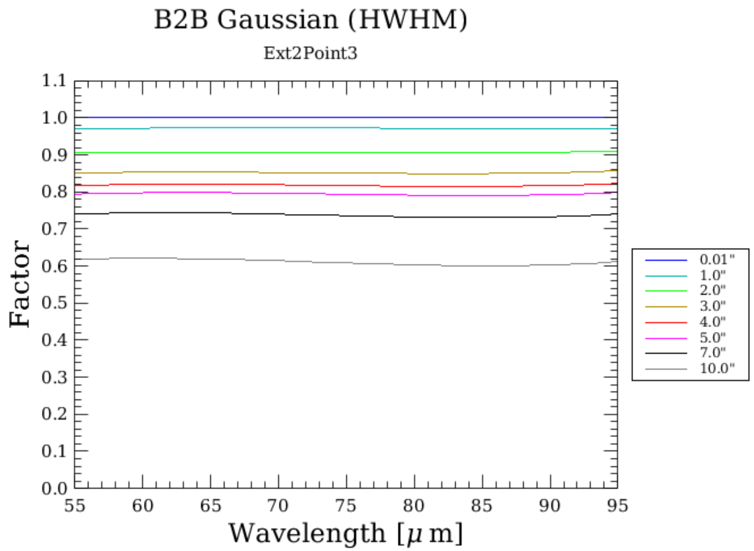


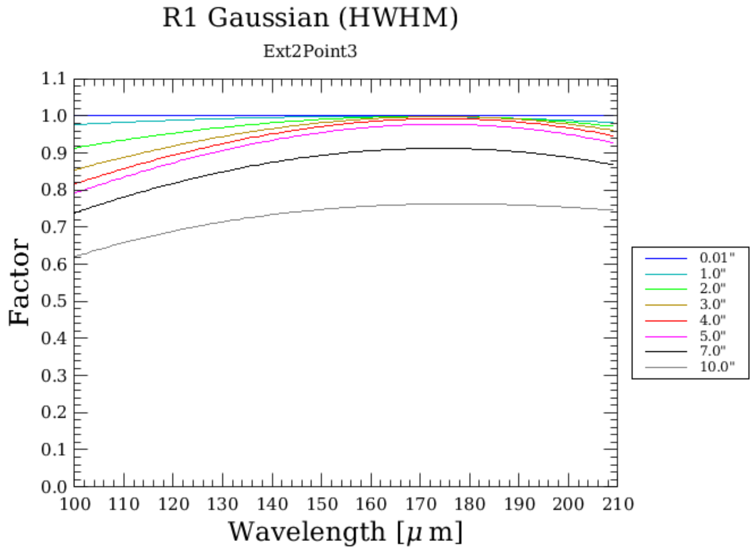


E2P Corrections: Gaussian









specExtendedToPointCorrection

- The task parameter central3x3=True/False produces two possible corrections:
  - E2P1: For extracted spectrum in central spaxel (c1)
  - E2P9: For extracted spectrum in central 3x3 spaxels or “superspaxel” (c9, c129)

$$F_s = I_{ext} . C_{point} \cdot \frac{1}{C_{cen\lambda}} \qquad F_s = I_{ext} . C_{point} \cdot \frac{1}{C_{3x3\lambda}}$$

```
result = divide(ds1=PointSourceSpec, ds2=ExtendedCorrection)
```

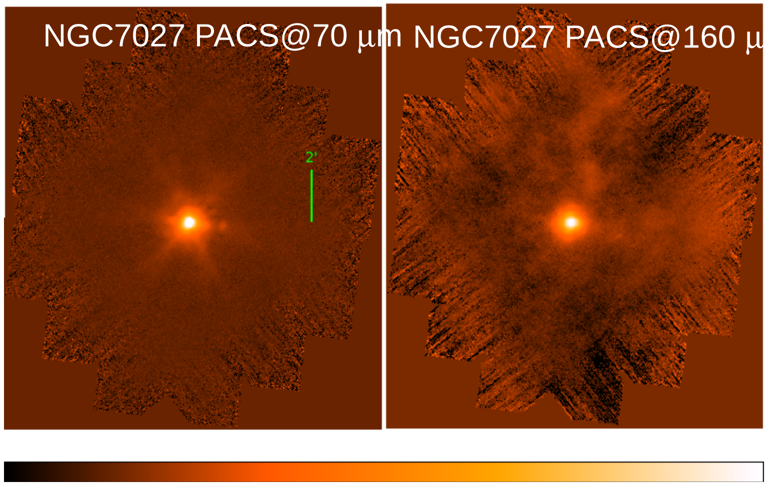
E2P Correction in post-processing steps

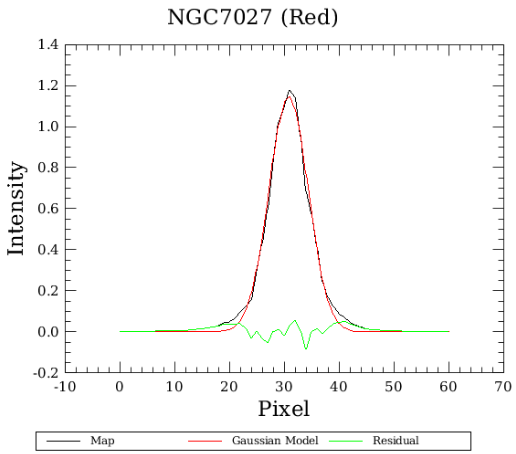
- Extends the decission tree described previously for the point source calibration correction:
  - Better Signal-to-noise ratio (C1)
  - Robustness against flux loss due to mispointing (C9)
  - In case of enough signal at both central spaxel and central 3x3 (~5-10 Jy), one can get the best of both worlds! (C129)

  ...with the additional element introduced by the source brightness distribution model in E2P
  - E2P1/E2P9 render a different amount of correction
- Comparison of all final spectra in each science case is central

Hands-on #1:

- Application of the specExtendedToPoint correction on PACS spectra of a strong continuum source
- Source: NGC7027 Protoplanetary Nebula
- Observations: SED mode
- Local data, Ipipe processing: Telescope Background Normalization, flatfield(excludeLeaks=1)
- Obsids: 1342186968, 1342186969
- Source Model: Gaussian FWHM=12¨

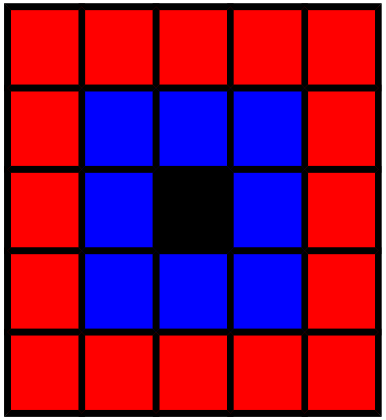


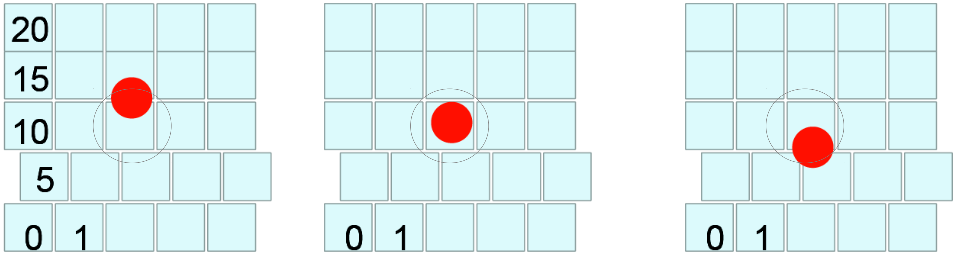


Limitations on the E2P Correction

- Source dimensions: this correction works best for sources whose spatial extent is smaller than the central 3x3 spaxels (i.e. ~30")
- Models derived from photometer maps may be dominated by the source's continuum emission:
  - Continuum: Is an average model representative of the source structure at all wavelengths?
  - Lines: Does line emission spatially follow the continuum emission? e.g. forbidden fine-structure lines trace the diffuse gas, that likely extends farther out.
    - This effect may be possible to be identified in strong continuum sources (Example: NGC7027 [OI] and [CII])

Concentration plot:
Average spectrum in the spaxels of each ring around central spaxel





Photometry information

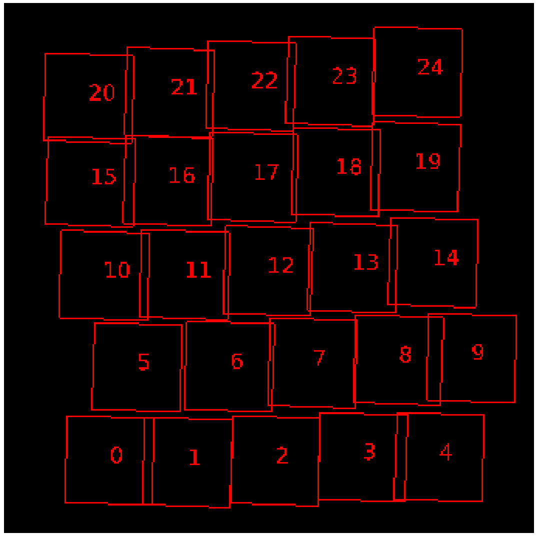
- I will use HSA products (photProject maps), JSCANAM maps will be available soon in 12.1 bulk reprocessing as archive products. Applicable to other mappers.
- Large aperture photometry to encompass the total source flux, using rectangular sky aperture for background determination.
- Color corrections should be ideally applied on photometric points, but only with sufficient photometric points (PACS and SPIRE)

Hands-on #2:

- Large aperture photometry
- Source: NGC7027 Protoplanetary Nebula
- Observations: PACS photometer maps (70, 160 micron)
- Obsids: 1342195839, 1342195840
- SPG product level 2.5 -photProject Maps
- Aperture Radius= 100”, rectangular sky background 90”x80”

Even More Extended Sources

- For sources larger than the 3x3 central spaxels, E2P correction is no longer valid, due to the finite size of the measured beam efficiencies.
- If the source spectra in the 5x5 spaxels are very similar, it is preferrable to use PACS photometric information to create an ad-hoc correction for the fraction of the source flux density that the IFU is missing.
  - Sum the spectra of all 5x5 spaxels in the PACS rebinned cube
  - Fit modified blackbody flux density distribution to photometric points
  - Fit modified blackbody flux density distribution to global spectrum
  - Correction=[s(λ)phot fit]/[s(λ)spec fit]



Hands-on #3:

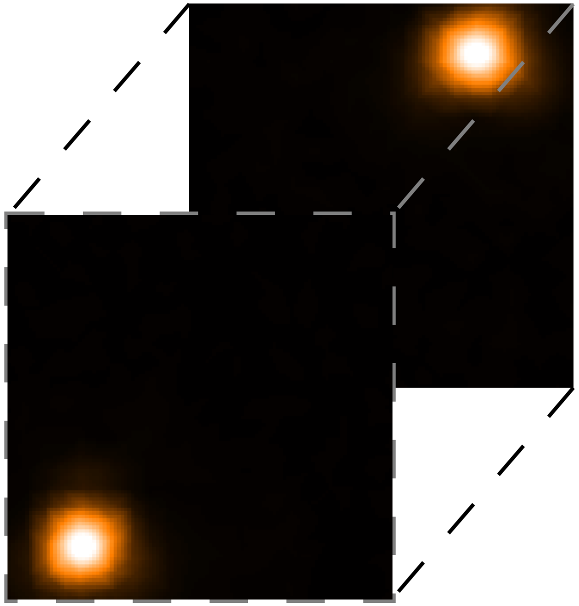
- Photometry assisted point source correction of large sources (larger 3x3 central spaxels)
- Source: Sh2-104 IRS1 globule at the ridge of a bubble
- Observations: PACS photometer maps (70, 100, 160 micron)
- Spec Obsids: 1342210815, 1342210816
- Local data, Ipipe processing: Telescope Background Normalization, flatfield(excludeLeaks=0)
- Phot Obsids: 1342185575,1342219040
- SPG product level 2.5 -photProject Maps
- Aperture Radius= 35”, rectangular sky background 90”x80”

PACS Beam Efficiencies

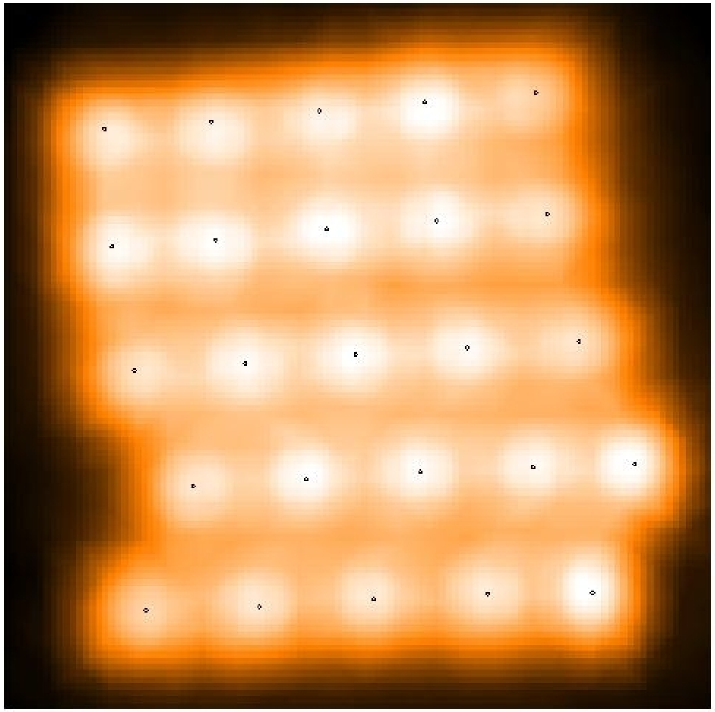
- Beam efficiencies at certain wavelengths (v3 interpolated beams) are located in calTree

  calTree.refs["spectrometer"].product.refs["beamsPerSpaxelX"].product

  with X corresponding to the band
- The beams are normalized to the fitted peak of the central spaxel beam



B2B 84 um



Sky Model Projection on beam

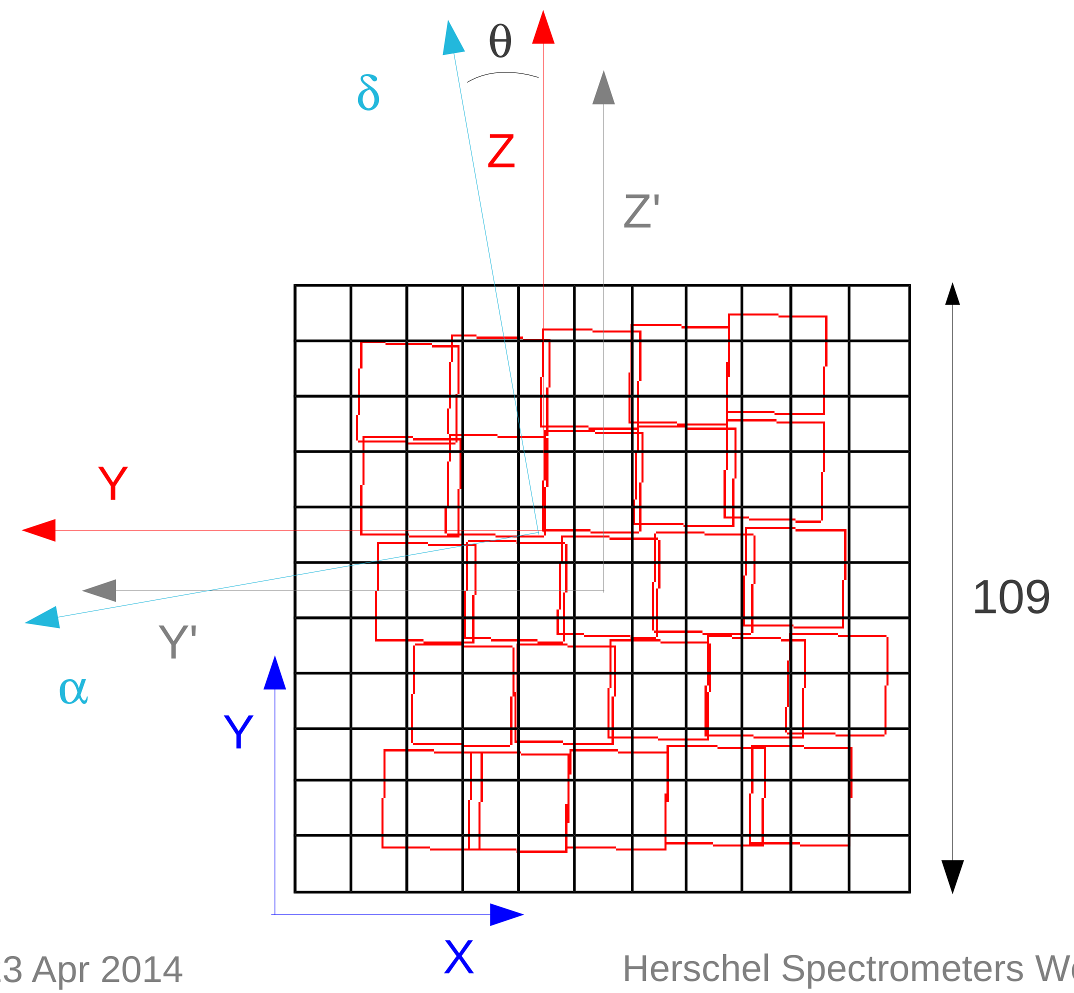
- Beam efficiencies of dimensions (M,N)=(109,109) in spacecraft coordinates (Y,Z, PA=0) relative to the central spaxel (k=2,l=2) and pixel scale of d_{pix}=0.5”

$$B_{klij\lambda}$$

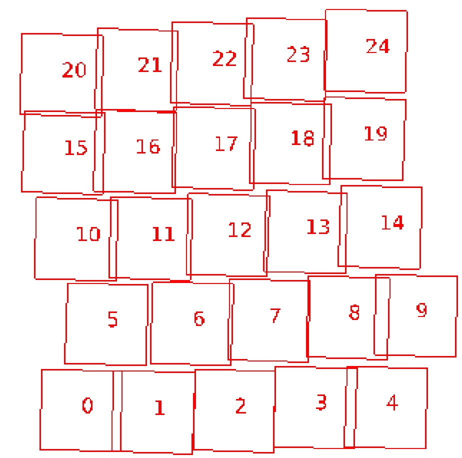
- Sky surface brightness model in relative R.A. and Dec coordinates in arcseconds from the centre of the sky map

$$S(\alpha,\delta)$$

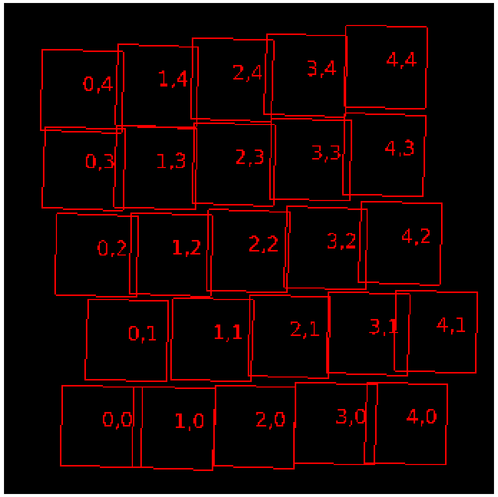
- Evaluation of model on beam grid S_{ij}



Modules

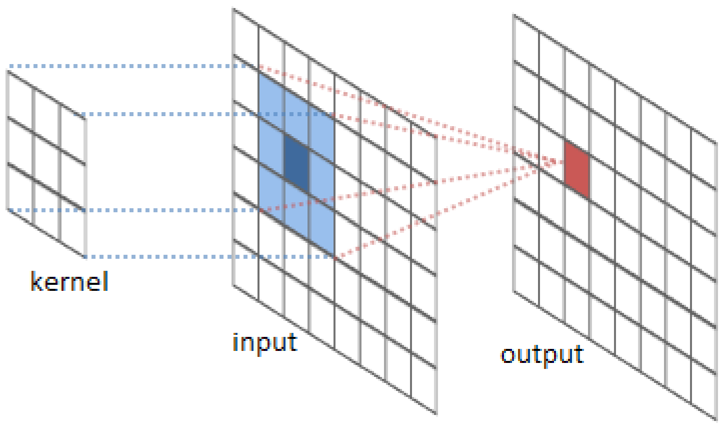


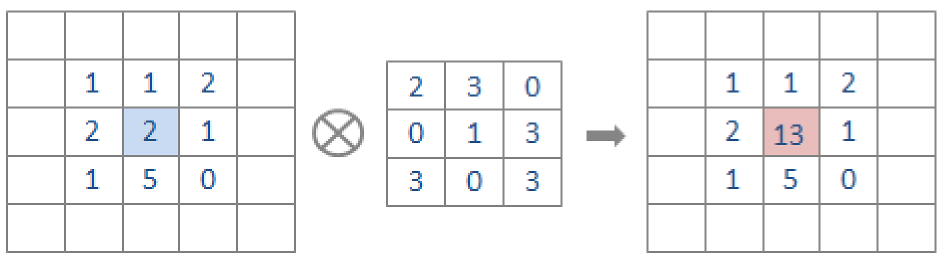
Spaxel Indices k,l



Model and Beam efficiency

- As the PACS beam efficiencies are maps, the surface brightness distribution should be similar to a 2D discrete convolution





The weight sum for this element is:
(1*2) + (1*3) + (2*0) +
(2*0) + (2*1) + (1*3) +
(1*3) + (5*0) + (0*3) +
= 13.

The PACS individual beam efficiencies have been calculated centred on each individual spaxel, Therefore, instead of convolving (by shift and multiply), the user just needs to multiply the model with each of the beam efficiencies of the 25 spaxels for each wavelength.

- Pseudo 2D discrete convolution with the individual responses of the k, l detectors/spaxels

$$F_{kl\lambda} = \frac{\sum_{ij} B_{klij\lambda} S_{ij}}{\sum_{ij} B_{klij\lambda}}$$

Hands-on #4:

- Simulation of PACS-S observations using a sky surface brightness model (photometer Map)
- Source: NGC7023 (extended emission around a Herbig Be star)
- Observations: surface brightness model (PACS photometer map at 160 micron) to compare to PACS spectrometer at a specific wavelength (145 micron)
- Phot Obsids: 1342187078
- SPG product level 2 -photProject
- Spec Obsids: 1342222230
- HSA level2 pacsRebinnedCube

PACS Beam solid angle truncation