PACS Observing strategy

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Instrument Concept

- **Imaging photometry**
  - two bands simultaneously (60-85 or 85-130 µm and 130-210 µm) with dichroic beam splitter
  - two filled bolometer arrays (32x16 and 64x32 pixels, full beam sampling)
  - point source detection limit ~3-4 mJy (5σ, 1h)

- **Integral field line spectroscopy**
  - range 57 - 210 µm with 5x5 pixels, image slicer, and long-slit grating spectrograph (R ~ 1500)
  - two 16x25 Ge:Ga photoconductor arrays (stressed/unstressed)
  - point source detection limit 3…20 x10^-18 W/m² (5σ, 1h)
1. PACS photometer AOT

- Science with PACS photometer
  - Sensitive mapping in 3 bands sampling the peak of SED for Embedded proto-stars
  - Re-emitted dust from AGNs and other extragalactic sources
  - Unprecedented spatial resolution at sub-mm wavelengths
PACS Photometer

- Relatively small rectangular 2×1 foot print, FOV = 3.5'×1.75'

- 2 channels simultaneously imaged (dual-band):
  - Blue channel 64×32 array, pixel size = 3.2", 60-85 \( \mu m \) or 85-130 \( \mu m \)
  - Red channel 32×16 array, pixel size = 6.4", 130-210 \( \mu m \)

- Sensitivity:
  - point source 5\( \sigma \)-1 hour
    - 3.5 mJy at 70 and 100\( \mu m \)
    - 5.0 mJy at 160\( \mu m \)
  - 1sq.deg. to ~10mJy 5\( \sigma \):
    - ~ 40 hours at 70 and 100\( \mu m \)
    - ~ 80 hours at 160\( \mu m \)

- PSF FWHM: 5.2", 7.7" and 12" in the 3 bands.

- On-board readout frequency: 40Hz
- On-board averaging, downloaded frequency: 10Hz, to stay within allocated 130kb/s rate.
Photometer system transmission

PACS photometer system transmission

Wavelength [μm]

transmission

75 μm (70 μm) 110 μm (100 μm) 170 μm (160 μm)
Photometer observing modes

General rules for which mode to use when:

• The size of mapped region usually determines which mode is more efficient
  • 1. Point-source mode: unresolved single sources
  • 2. Small-source mode: single source <1’-1.5’ in size
  • 3. Chopped raster: sources >1’ and <12’
  • 4. Scan maps: Source > 10’

• Exceptions: (always!)
  – You might want to use scan for area <12’ if chopped negative beams do not suit your needs, esp. close to the confusion limit.
  – Use scan if you are worried about your off position.
Photometer AOT concept

**Point source photometry:**
- 4-point chop/nod cycle
- Any orientation possible

**Extended source Mapping:**
- Scan or Raster
- Chopping optional with rasters

**Small source photometry:**
- Small MxN raster
- Chopping optional
- 2x field of view
- Fixed step sizes
- Any orientation
1.1 Point-source mode

- Targeted at observations of sources which are completely isolated and point-like or smaller than one blue matrix.
- Uses chopping and nodding, both with amplitude of 1 blue matrix, and dithering with a 1 pixel amplitude, keeping the source on the array at all times.
- Possibility of dithering with chopper.
- Minimum execution time: 5.5 min (incl. 3 min for slew).
- Predicted sensitivity (5σ):
  - 70/110 μm: 15 mJy
  - 170 μm: 22 mJy
1.2 Small-source photometry mode

- Observations of sources that are smaller than the array size, yet larger than a single matrix.
- To be orientation independent, this means sources that fit in ~1.5’x1.5’.
- Off-array chopping, nodding, dithering to fill gaps.
- Minimum execution time: 15min
  - (incl. all slew overheads).
- Predicted sensitivity (5σ):
  - 70/110 µm : 10mJy
  - 170 µm : 15mJy
Small-source chopping/nodding

Double difference, to subtract telescope foreground
1.3 PACS large area mapping

- However Herschel was designed to make large scale surveys: to map sources larger than the array size, or cover large contiguous areas of the sky (photometric surveys), two modes are available:

  - **Raster mapping** the satellite goes through a rectangular grid pattern of points in internal reference frame (that can be repeated).
    
    Note: Rastering only with chopping (1/f noise)

  - **Scan mapping** (without chopping): the satellite slews continuously along parallel lines at constant speed (10, 20 or 60 arcsec/s)
    
    - Filled arrays allow (almost) arbitrary scanning orientation
    - 1 square degree in a few hours (at 10″/s)
1.3.1 Raster mapping

• Modulation of signal necessary because of 1/f noise
• Hence chopping imposed at 0.25Hz
  – Given by Allan variance (blue array), probably less later as compromise between blue and red detector
• Duration per raster point fixed at 64s (8 on/off cycles)
• Chopper-throw fixed at 3.5 arcmin, i.e one FOV (long side)

• Raster mapping only allowed in instrument reference frame
  ➔ orientation depends on position angle of day of observation
  ➔ to be immune against PA (position angle) rotation, it is advised to define square maps
Raster mapping concept

- Map centered on the area mapped by the chop/on footprints

- SRPE=Spatial Relative Pointing Error
  - Current performance prediction = 2.0 arcsec,
  - Requirement/goal: 1 arcsec
Raster limitation 1: slew times overhead

- Observation efficiency limited by the duration of small slews between raster points,
  - typically of the order of 20-30 sec..
  - $\sim \frac{1}{3}$ of overheads for small slews
Raster limitations (2)

• **Chopping:**
  – introduces negative sources/beams
  – degrades the sensitivity by $\sqrt{2}$ because of differential imaging
  – and another factor $\sqrt{2}$ because if sources seen only in one chop position (as half of the time spent on source).

• Only relatively small areas can be mapped, up to 10'x10' or 15'x15'

∞ → For larger area: scan mapping
1.4 Scan mapping

- For large areas up to several square degrees, no-chopping
- 3 scan speeds
  - Slow: 10”/s, for extragalactic mapping/surveys
  - Medium: 20”/s, for larger areas >1 sq.deg
  - High: 60”/s, for galactic surveys
- PSF degradation:
  - Shift and broadening of the PSF because of electrical (and thermal) time constants and 10 Hz averaging: minimal at slow and medium speed
  - Significant impact at the high speed, broadening by a factor 2.
- SRPE along a line = 2.0 arcsec
Scan mapping efficiency

- Large overhead for turn-around manoeuvre between scan legs
- Scan legs smaller than 15’ are very inefficient.
- Significant reduction to be achieved for GT KP phase II entry and OT KP call by a factor ~2 at the expense of a marginal degradation of attitude accuracy along a scan leg.

![Graph showing PACS scan mapping efficiency](image)
Scan maps orientation

- **With filled array, no fixed magic angle like SPIRE**
- **Two types of scan maps**
  - 1/ in instrument reference frame
    - Advantage: control on the geometry of the scan map
    - Drawback: control on map orientation, only via constraints
      - orientation constraint or
      - timing constraint in HSpot (not advised)
    - Not always possible and 10mn penalty
    - Hence maps shall be square
  - 2/ in sky coordinates
    - Advantage: control on map orientation
    - Drawback: limited control on homogeneity of the scan map
      - but with PACS 'magic distance': cross-scan distance of a blue matrix 51 arcsec, the coverage is rather homogeneous, whatever the array to map angle
Scan map orientation

- In reference frame “array” in HSpot
  - $\alpha$ fixed, constraint on $\beta$ is possible
  - Selection of homogeneous coverage offered in HSpot.

- Oriented in the sky, “sky” in HSpot
  - $\beta$ fixed, constraint on $\alpha$ possible

- Note: If $\alpha=45^\circ$ then orthogonal coverage has same depth

$\alpha = \text{array-to-map angle}$
$\beta = \text{map orientation angle}$
$PA = \text{array position angle}$
$\beta = \alpha + PA$
Scan maps in HSpot
- Exposure map tool in HSpot (NHSC).
- Useful to check homogeneity
- *See tomorrow’s demo.*
2. PACS spectroscopy AOTs

- Line Spectroscopy (of individual lines)
  - Line scan
  - Bright line scan
    - Similar to line scan with fewer grating steps (16 instead of 44)
  - Wavelength switching

- Range spectroscopy
  - User-defined range spectroscopy
    - 2 spectral sampling densities:
      - High: 1/3 FWHM steps
      - Low: each wavelength seen by two different spectral pixels
  - SED spectroscopy (range spectroscopy applied to the entire observable spectrum)
    - only in low spectral (Nyquist) sampling
• **Line Spectroscopy:** observation of individual line(s)
  – Chop/nod or wavelength switching
  – Staring or mapping
  – $R \approx 1500$

• **Range Spectroscopy:** observation of extended range(s)
  – Chop/nod or off position
  – Staring or mapping
  – SED mode

Instantaneous spectral coverage: 0.15 to 1 $\mu$m
Science with PACS Line Spectroscopy

• The opening of the 60-210 μm window by PACS to sensitive line spectroscopy at high spatial resolution will address a wide range of key questions of current astrophysics concerning the origins of stars, planetary systems, galaxies, and the evolution of the Universe

• The far-IR contains many spectral lines from atoms, ions and molecules. Largely unaffected by extinction they provide detailed information on UV radiation, density, temperature, velocities and abundances of ionized and neutral components of interstellar and circumstellar gas

• PACS is also intended to be an important driver for other projects which will explore adjacent spectral regions, such as JWST in the near/mid IR and ALMA in the mm domain
Spectral resolution

\[ \frac{\lambda}{\delta \lambda} = 940-5500 \]
\[ c \frac{\delta \lambda}{\lambda} = 55-320 \text{ km/s} \]
2.1 Line Spectroscopy in chopping/nodding

AOT implementation
Line Spectroscopy in chop/nod – AOT implementation

Spectral sampling >3 samples/FWHM (by small up/down scan)
First PACS (Laser) Line Spectrum!
2.2 Line Spectroscopy in λ-switching

AOT implementation
Grating frequently switched between two positions
Same pattern repeated several times at slightly shifted wavelength

wavelength [µm]
Line spectroscopy pointing modes

- **POINTED**: single satellite pointing
  - with chopping/nodding except in wavelength switching
  - Fixed chopper throw: 1, 3 and 6 arcmin
- **POINTED WITH DITHER**: small spacecraft movements perpendicular to the chopper direction to compensate for slicer effects in case of slightly mispointed targets
- **MAPPING**: limited to rectangular small regions with a maximum extension of 6 arcmin to allow for clean chopper off-positions for each raster point
  - map parameters in instrument coordinate system except in wavelength switching

- Order 1: 102 – 210 μm
- Order 2: 72 – 96 μm
- Order 3: 55 – 72 μm
Example 1:
Spectroscopic line survey of a galaxy (no mapping)
5 lines (2nd and 1st order), chop/nod, rep=1, cycle=1, medium throw
(to this the time for the 2 lines in 3rd order has to be added - concatenation)
Example2:

Spectroscopic line mapping of a galaxy (M82)

E.g. map transition from the central starburst to the molecular ring to quiescent disk along major axis in NIII/NII.

E.g. map cooling of gas and shock vs. ionization along super wind outflow in CII/OI
5 lines (2nd and 1st order), chop/nod, rep=1, cycle=1, medium throw, 3x1 map
## Chopping/nodding vs wavelength switching

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>chop/nod</td>
<td>- not for large extended sources (&gt;6‘x6‘), or crowded fields</td>
</tr>
<tr>
<td></td>
<td>- map orientation only via orientation constraint</td>
</tr>
<tr>
<td>chop/nod</td>
<td>- preserve continuum</td>
</tr>
<tr>
<td>- also for extended or crowded fields</td>
<td></td>
</tr>
<tr>
<td>- map orientation can be chosen</td>
<td></td>
</tr>
<tr>
<td>- slightly more sensitive as target always on array</td>
<td></td>
</tr>
<tr>
<td>- less severe memory effects for bright lines ?</td>
<td></td>
</tr>
<tr>
<td>λ-switching</td>
<td>- continuum lost</td>
</tr>
<tr>
<td>- z must be known precisely</td>
<td></td>
</tr>
<tr>
<td>- mode to be confirmed for faint sources</td>
<td></td>
</tr>
</tbody>
</table>
pointed vs. pointed with dither

- flux reconstruction of (faint) point sources might be improved with dither if the source position is uncertain, and/or the source is slightly extended (pointing uncertainty!)
- small raster might be better, anyway, in these cases
  - 2x2 raster, 4.5“ arcsec step size.
- clear guidelines cannot be given at this point in time
- the exact dither/map pattern and the overlap between pointings, is perhaps not overly important (pointing uncertainty! data processing needs to start from after-the-fact reconstructed pointing information anyway)
3. Range spectroscopy

- Same basic idea as in line spectroscopy
- on a wider, user-defined spectral range
- possibility to use lower grating sampling density
- SED mode to cover whole PACS wavelength range
- Same pointing modes
Parallel ranges

Different grating orders are observed simultaneously in red and blue detector.

- **Order 1+2**
  - 102-210 μm
  - // : 71-96 μm

- **Order 1+3**
  - 102-210 μm
  - // : 55-73 μm

Spectrometer wavelength calibration (FM_1_0)
Parallel ranges: examples

- Range scan 60-70 μm [order 3]
  - yields 'for free' range in order 1: 180-210μm
- Range scan 72-80 μm in [order 2]
  - yields 'for free' range in order 1: 144-160μm
- Range scan 120-180 μm [order 1]
  - If range [71-98] is selected, yields for free:
    - 71-90 μm [order 2]
      [order selection filter: cut-off short of 72μm]
  - If range [55-73] is selected, yields for free:
    - 60-73 μm in ‘extended’ 2nd order and
    - 55-60 μm in order 3.

- All parallel ranges and sensitivities returned by HSpot, graphically
Full range scan in SED modes.

- **PACS full range scan**
  - 2 concatenated AORs as no filter wheel change allowed in one aor,
  - pre-defined full range scans
- **SED red [71-210] μm, in 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) order:**
  - order 1 : 102-210 μm
  - order 2 : 71 - 98 μm
    - [order selection filter: cut-off short of 72μm, and dichroic at 98μm]
- **SED blue [55-73] μm in 3\(^{\text{rd}}\) order and partially 1\(^{\text{st}}\):**
  - order 3 : 55 – 73 μm
  - order 1 : 165 – 219 μm
- **SED blue high (continuum) sensitivity in extended 2\(^{\text{nd}}\) order:**
  - order 2 : 60 – 73 μm
  - order 1 : 120 – 146 μm
Two spectral sampling densities

- **Nyquist sampling**
  - Unresolved line FWHM Nyquist sampled
  - Nyquist considering all 16 spectral pixel
  - This sampling is chosen for SED mode (PACS full range AOR)

- **High Sampling**
  - Spectral sampling as in line spectroscopy
  - ~3 samples per FWHM in every detector
Nyquist sampling (SED)

- 4 scans in 1 telescope nod cycle
  - 1 up / 1 down wavelength direction
  - Repeated on 2nd nod position
- Duration, e.g. full range
  - 102 - 210 μm (71-98 for free) : 1121 s (“SED red”)
  - 55 – 73 μm (extra 165-219 free): 847 s (“SED blue”)
  - Repetition factor 2: so total PACS range in 1 hour.
- Sensitivity (line / continuum)
  - Varies over wavelengths
  - Increase S/N : repeat nod cycle
SED predicted sensitivities

RMS continuum PACS SED range scan

RMS [Jy]

Wavelength [μm]

5.0 \times 10^{-17}

2.5 \times 10^{-17}

1.5 \times 10^{-17}

1.0 \times 10^{-17}

5.0 \times 10^{-18}

0.0

Wavelength [μm]

line RMS PACS SED range scan

RMS [W/m²]
High sampling

• 4 scans in 1 telescope nod cycle
  – 1 up / 1 down wavelength direction
  – Repeated on 2nd nod position

• Duration, e.g. full range
  – 102 - 210 μm (71-98 for free) : ~18611 sec
  – 55 – 73 μm (extra 165-219 free): ~17151 sec
  → total: ~10 hours

• Sensitivity (line / continuum)
  – Varies over wavelengths
  – Increase S/N : repeat nod cycle
High-sampling predicted sensitivity
Questions?


- Herschel Helpdesk: http://herschel.esac.esa.int/esupport/