PACS Photometer - Chopping Modes: Point-Source, Small-Source & Large Raster Mode

The PACS ICC

This document provides a brief summary of the relevant performance parameters of the chopped observing techniques in the PACS photometer and the corresponding release status:

- Point-source chopped-nodded mode (with/without dither-option): **released**
- Small-source chopped-nodded 2×2 raster mode: **cancelled**
- Large-source chopped raster mode: **validation currently not foreseen**

Instead of small-source and large raster modes we recommend to use the PACS photometer scan map mode. In case of point-sources the PACS scan map mode can also be considered as a valid alternative with similar performance regarding expected SNR, despite the large overheads for satellite turnarounds (see section 4.3 for implementation details). Based on our current data reduction experience, our knowledge on detector noise behaviour in this mode and the presence of background confusion, the faintest detectable flux is larger than the HSPOT prediction. For sources above ∼10 mJy the performance is worse than the HSPOT prediction by roughly a factor of 1.5.

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1 Point-source chopped-nodded observations

1.1 Technical implementation: Calibration Block and On-Sky

The calibration block is executed during the target acquisition phase and lasts for about 30 s. The chopper moves with a frequency of 0.625 Hz between the two PACS internal calibration sources. 19 chopper cycles are executed, each chopper plateau lasts for 0.8 s (32 readouts on-board) producing 8 frames in the down-link. There are always 5 s idle-time between the calibration block and the on-sky part for stabilisation reasons.

The calibration blocks allow to follow the evolution of the bolometer gains during the day. There is always one such block at the beginning of each PACS photometer AOR (also in cases of grouped/concatenated observations). This single calibration block is sufficient, even for very long observations. Note: The longest possible duration of a point-source AOR in chopping-nodding techniques is 5.55 h in case of the maximum allowed repetition factor of 120.

The PACS photometer point-source mode uses the Pacs chopper to move the source by about 50″, corresponding to the size of about 1 blue/green bolometer matrix or the size of about half a red matrix, with a chopper frequency of 1.25 Hz. The nodding is performed by a satellite movement of the same amplitude but perpendicular to the chopping direction. On each nod-position the chopper executes 3×25 chopper cycles. The 3 sets of chopper patterns are either on the same array positions (no dithering) or on 3 different array positions (dither option). In the dither-option the chopper pattern is displaced in ±Y-direction (along the chopper direction) by about 8.5″ (2 2/3 blue pixels or 1 1/3 red pixels). Each chopper plateau lasts for 0.4 s (16 readouts on-board) producing 4 frames per plateau in the down-link. The full 3×25 chopper cycles per nod-position are completed in less than 1 minute. The pattern is repeated on the second nod-position. In case of repetition factors larger than 1, the nod-cycles are repeated in the following way (example for 4 repetitions): nodA-nodB-nodB-nodA-nodA-nodB-nodB-nodA to minimise satellite slew times.

1.2 Sensitivity estimate

The currently achieved sensitivity is worse than the HSPOT prediction. This is not due to increased noise in the instrument. The most likely causes of this are:

1. a too simple approach in the sensitivity estimate to take into account $1/f$ noise: the effective actual noise level with 1.25 Hz chopper frequency and 4 readouts per chopper plateau is higher than the adopted 3 Hz value of the 1/f noise spectrum assumed in HSpot predictions.
2. the actual optical coupling of the instrument to the sky,
3. the detector time constants which affect the first frame after each chopper transition and hence the detector responsivity. Currently, 25% of the data are discarded for that reason,
4. combination of all effects.

The noise spectrum is such that higher sensitivities would be reached for faster chopper frequencies, but due to the detector time constants the signal losses increase in a way that for a given AOR execution time the sensitivity would not improve.

Based on our current data reduction experience, our knowledge on detector noise behaviour in this mode and the presence of background confusion, the faintest detectable flux is larger than the HSPOT prediction. For sources above ∼10 mJy the performance is worse than the HSPOT prediction by roughly a factor of 1.5.

1.3 Pipeline status

The pipeline data-processing steps (apart from the obvious ones such as unit conversion and astrometry addition) are (see more details in the PACS User's Manual):

flag known bad pixels

flag saturated pixels

convert ADUs to Volts

correct for cross-talk (currently disabled)

assign Ra/Dec to each pixel

signal averaging per chopper plateau (discard first frame of each plateau)

difference of chopped signals and cosmic rays removal

signal averaging per dither position

difference of nod-positions per dither position

combination of dither-positions

Responsivity and flat-field correction

Gain drift correction (currently disabled)

Map reconstruction

Cosmic rays removal is performed with a sigma-clipping when averaging at each dither position. Cross-talk correction (affecting mostly one column on both red matrices) is implemented, but not validated yet as we are generating the calibration file needed for the pipeline module. Responsivity, flat-field, gain drift corrections use ground-based version of the calibration product and will be updated in the course of the Science Demonstration Phase. Map reconstruction is a simple projection of the data cube after shift & add of the 4-beam chop-nod pattern.

The final map covers about $2.5' \times 4.5'$, but with uneven coverage and beam pattern. Only the central $\sim 50'' \times 50''$ receive full coverage and correct addition of beams of the targeted source, other regions can help diagnosing contamination by other sources in the field.

2 General photometer aspects

2.1 Point spread function

The photometer PSF is characterised by:

- A narrow core which is round in the blue bands but slightly elongated in spacecraft Z direction in red.
- A tri-lobe pattern seen at the several % level in all bands, most clearly in the blue with its strongest signal, and ascribed to imperfect mirror shape.
- Knotty structure at sub-percent level, clearly seen in blue and indicated in green.

An illustration of the PSF is shown in Figure 1.

These PSFs and derived quantities reflect the intrinsic optical quality of Herschel+PACS. In the chop-nod point-source reduction they will be slightly smeared, in particular at short wavelengths, according to telescope pointing jitter and drifts.

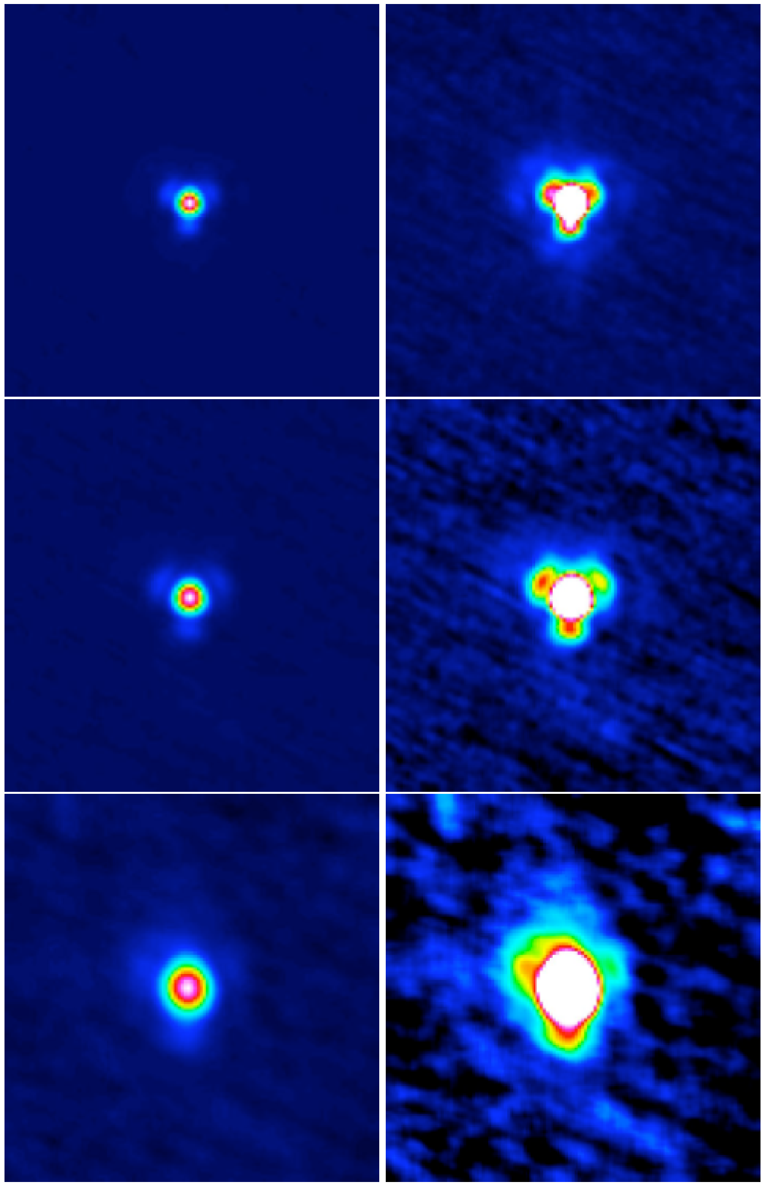

Figure 1: The photometer PSF in blue, green and red (top to bottom) derived from scans performed at 10 ″/s. Left-hand panels display the image with a linear scale up to the peak, while right-hand panels show up to 10% of the peak.

2.2 Flux calibration

The flux calibration factors currently in place in the PACS photometer pipeline are still those defined in the ground-based calibration campaign. It should be noted that flux calibration of PACS photometer data is a three-stage process: the data have to be flat-fielded, engineering units are converted to Jy/pixel (the responsivity correction), and pixel gains are corrected for with respect to a reference consistent with both the flat-field and the responsivity calibration products (to account for small gain drifts with time).

Currently the fluxes are a factor 1.5-2 systematically too low. But a first rough flux estimate can be obtained by multiplying the pseudo-Jansky in the final maps by factors of 1.8 (blue 70 μm band band), 1.5 (green 100 μm band) and by 1.4 (red 160 μm band). This large uncertainty will be significantly decreased when inflight calibration data replace the ground-based ones, which should happen toward the end of the Science Demonstration Phase.

2.3 Pointing

The Relative Pointing Error (RPE) is about $0.3''$ implying a high stability for the chopping phases. Due to the Spatial Relative Pointing Error (SRPE) of about $1.5''$ a slight broadening of the PACS PSF is expected when combining the images of the two nods, in particular in the blue/green bands where the PSF is sharper. The Absolute Pointing Error (APE), which affects the complete chop-nod pattern, is better than $2''$.

2.4 Digitization

Because of satellite data-rate issues, we have had to add a supplementary compression stage called bit-rounding before the data is down-linked. This means that while we average 4 images on board, we also round the last n bits of the result. The default value for n was 2 during the Performance Validation campaign (high-gain observations performed with bit-rounding of 2 are effectively digitized with a step of $2\,10^{-5}$ V, or 4 ADU), now released to 1 bit only since the Nov. 2, 2009.

The PACS ICC is currently experimenting with dispensing with this compression step in some observing modes. Finalisation of the bit-rounding mode will occur during Science Demonstration.

3 Discussion on the point-source mode

3.1 Caveats of chop-nod Point-Source mode

The implemented chop-nod technique has limitations in case of nearby sources (all 3 bands) and confusing background structures (mainly in the red band). In these cases the various chopped-nodded beams might overlap in the final map and accurate photometry is more difficult (see Fig. 2, left side).

The area of homogeneous coverage in the final image is limited to a region of side length 8-10 pixels around the source. Outside this region the noise properties are different due to a lower pixel coverage (see Fig. 2, right side).

The chop-nod technique relies strongly on the performance of very few pixels. Some of these key pixels are meanwhile known to show intermittent variability (column 11 in blue matrix 6), i.e. with potentially higher noise levels. It is not possible to completely avoid the bad pixels due to array size constraints, possible astrometric uncertainties for the science targets and the APE of the satellite.

The PACS chop-nod technique is not suitable for the follow-on option which was foreseen for moving solar system targets to catch the object a second time after it has moved by about 3 FWHM. The final map is too much disturbed by the various beams and the poorer pixel coverage at these distances from the map centre does not allow to fully characterise the background as it was planned via the follow-on option.

3.2 Advantages of chop-nod Point-Source mode

One advantage of the chop-nod technique is the stability of the reconstructed PSF due to the small RPE of $0.3''$.

We also expect that the chop-nod technique (in combination with the dither-option) will provide high photometric accuracy for isolated sources.

Many stellar calibration sources have meanwhile been observed in the described chopping-nodding technique during PV phase, allowing to reduce and calibrate the science target observations in a very controlled and reliable way.

The chop-nod mode allows to obtain very high spatial resolution which might be needed for resolving small-scale structures. But since there is no "cluster pointing-mode" available, such a sub-pixel (satellite) dithering is only

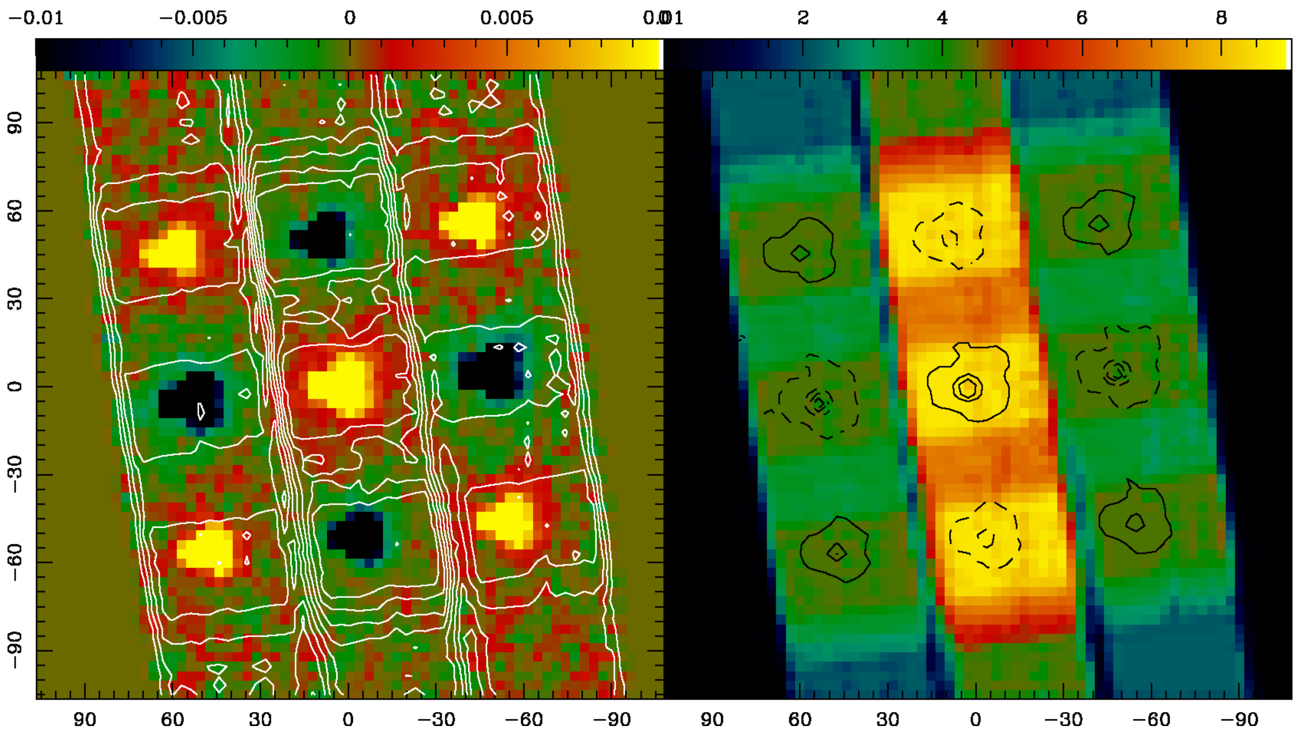

Figure 2: Synopsis of the final map (left) and the pixel coverage (right) after the final processing step with all chop/dither/nod positions projected onto the sky for a bright target with several Jansky. It demonstrates the limitation in aperture photometry to find clean background regions due to the various positive and negative beams. The coverage map illustrates that only a fraction of the central image of the target has the full pixel coverage.

possible by entering serveral concatenated/grouped AORs with slightly shifted target positions.

3.3 Chop-nod mode implementation for point-sources

The PACS ICC recommends using the dither-option to improve the PSF-sampling for fainter targets.

Due to symmetry reasons in the analysis of the nod-positions we recommend to use either a repetition factor of 1 (nodA - nodB) or a multiple of 2 for the repetition factor (example for a repetition factor of 4: nodA-nodB-nodB-nodA - nodA-nodB-nodB-nodA). The the analysis the data are then sliced by nod-blocks consisting of "nodA-nodB-nodB-nodA" and a later recombination of these slices.

4 PACS scan map mode for point-sources

Alternatively it is possible to use the PACS scan map mode also for point-sources. Despite the large overheads for the satellite turnarounds between the short scans, this option has a similar performance with respect to point-source S/N within the same AOR execution times.

4.1 Advantages of scan maps for point-sources

The advantages for the scan map mode are:

- it provides a better characterisation of the close vicinity of the target and larger scale structures in the background
- also targets with positional uncertainties of $10''$ or more are still perfectly covered
- the final map has a much larger area of homogeneous coverage (at least $2' \times 3.5'$ depending on observation configuration, see Fig. 3)
- more pixels see the target, the impact of noisy, variable and dead pixels is less problematic
- better point-source sensitivity in the blue/green bands as a high-pass filter can be used to remove 1/f noise up to higher frequencies.
- no negative beam in final map.

4.2 Disadvantages of scan maps for point-sources

The small array size requires the implementation of short scan legs of 3 to $4'$ only. Combined with the optimum scan speed of $20''/s$ this leads to short on-scan times of less than 12 s. The corresponding satellite turnarounds between these scan legs take currently about 30 s. It is expected that the large overheads for satellite turnover loops will be shortened by about 15 s in the near future (end Nov 2009), but the ratio between useful on-array time and satellite manoeuvre is still bad.

The scan direction combined with the array orientation produces image artefacts which are not present in the centre of the maps obtained by the chop-nod technique.

4.3 Scan map mode implementation for point-sources

In case of using the scan map mode for point-sources and very small fields we propose the following configuration:

- medium scan speed ($20''/s$)

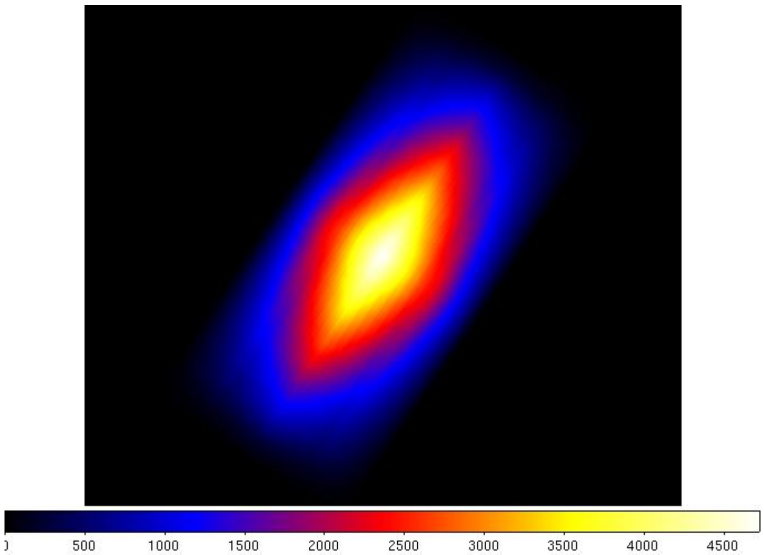

Figure 3: The coverage map for a mini scan map. For such a small map size (3.5 arcmin leg length and small cross-scan steps), the coverage map is very peaked towards the center where the point-source resides.

- scan angle in array coordinates along the array diagonal: 117° or 63°
  (in case of cross-scans: 117° and 63°)
- scan lengths: 3.0, 3.5 or 4.0′ (the array diagonal has about 3.9′)
- small and even number of scans: 4, 6 or 8 (for minimisation of satellite movements and a match to the array diagonal)
- small leg separation: 2...5″ with the smaller separation for a larger number of scan legs and vice versa (to have the source on-array in all legs)
- repetition factor: as needed to reach the required sensitivity
- cross-scan maps: would allow to apply all kinds of map-making techniques and not just the high-pass filtering. Probably also required for higher quality photometry and better spatial characterisation in the near source vicinity. It is recommended to group/concatenate the 2 cross-scan AORs to minimise slew overheads. Each AOR will have its own 30 s calibration block.

Note: Part of the satellite turnarounds are still containing useful information: For the $20''/s$ scan speed it is possible to use, in addition to the scan legs, about 0.8 s (i.e., 16″) prior to each scan leg and about 1.6 s (i.e., 32″) after the official scan leg has finished. During these times the scan speed is already/still very close to the requested value. The selection of 3.0′ legs (combined with $20''/s$) is therefore the optimal usage of the scan map mode (highest S/N). In this case the source would be on-array 100% of the observing time although it is questionable if the complete satellite turnaround (including deceleration, some idle-time and acceleration) will be useful in the analysis.

4.4 Direct comparision of both modes

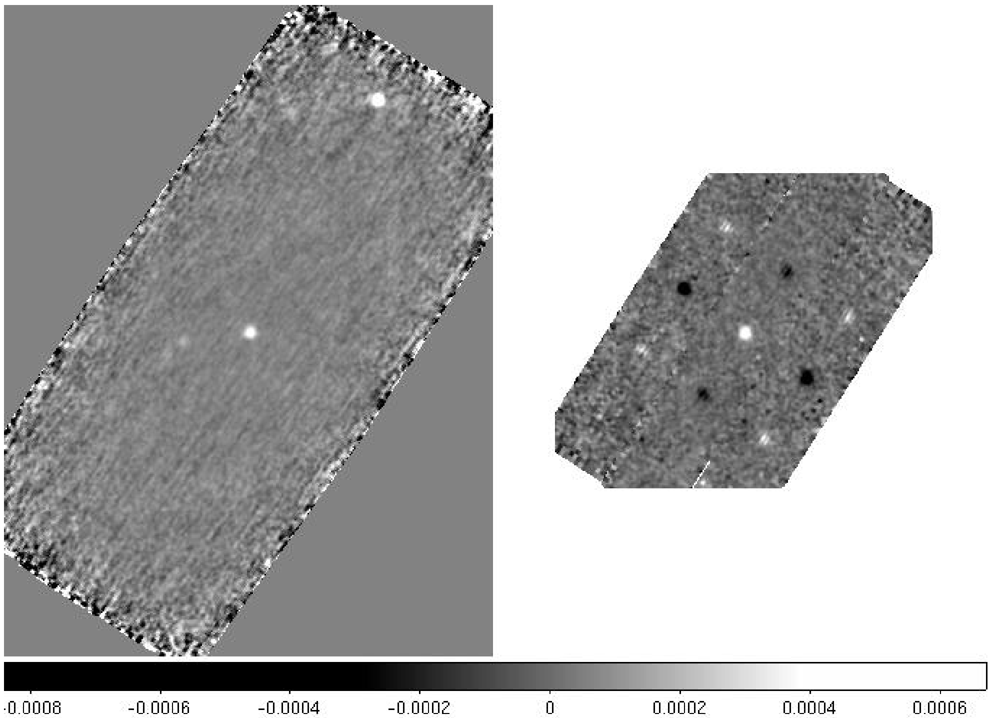

Figure 4: HD 1382865 (OD132) observed in scan-map mode (left) and chop-nod (right) for a similar AOR execution time in the blue band (70 μm), displayed with the same image cut levels

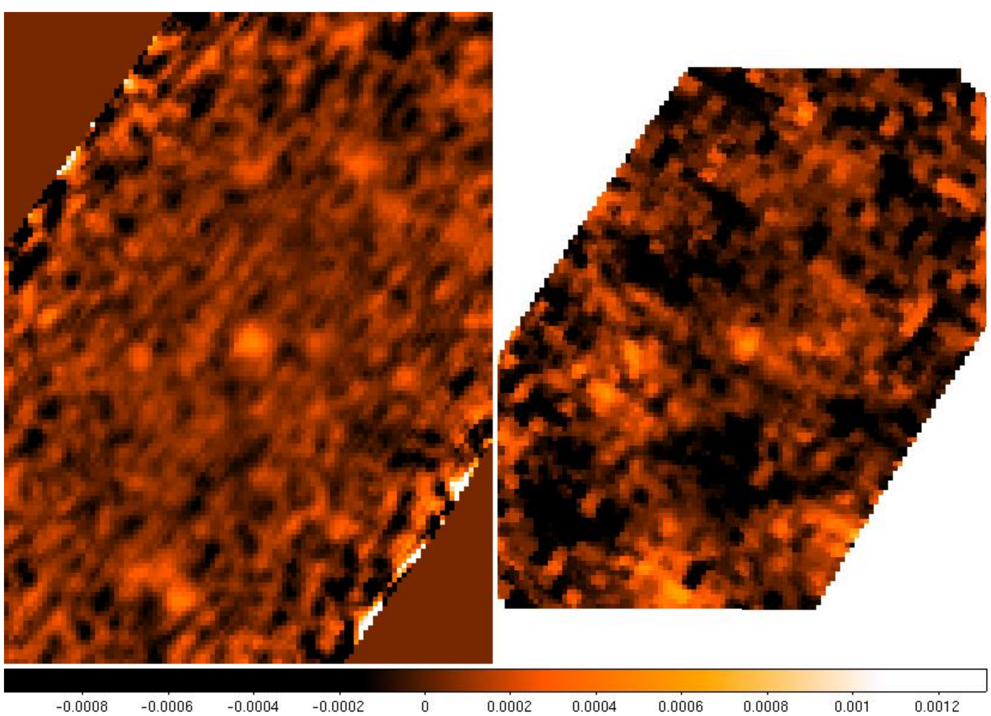

Figure 5: HD 1382865 (OD132) observed in scan-map mode (left) and chop-nod (right) for a similar AOR execution time in the red band (160 μm), displayed with the same cut levels.

5 Small-source Mode and Large Raster Mode

Both modes can be replaced by the Scan Map Mode implementation without loosing sensitivity performance. But for very small fields it is advisable to wait for the final optimisation of the satellite turnaround loops. A significant increase of on-source is expected when the idle-times during the turnaround loops are minimised. It is planned to have this change available towards the end of November 2009.

With this optimisation in the Scan Map Mode we consider the chopped-nodded Small Source Mode as obsolete. Already implemented observations should be moved to the Scan Map Mode following the implementation recommendations in Section 4.3. Nevertheless, several reference measurements in this 2×2 raster fields with off-array chopping and nodding are available as part of the photometer validation programme.

The Large Raster Mode, with the availability of a large range of possible steps and step sizes, has been executed during performance verification phase in different flavours. But in all considered cases the repetition of these fields in Scan Map Mode would provide more reliable products and in most cases also better sensitivity. It is currently not foreseen to commission this mode.