Optimized PACS photometer observing and data reduction strategies for moving solar system targets

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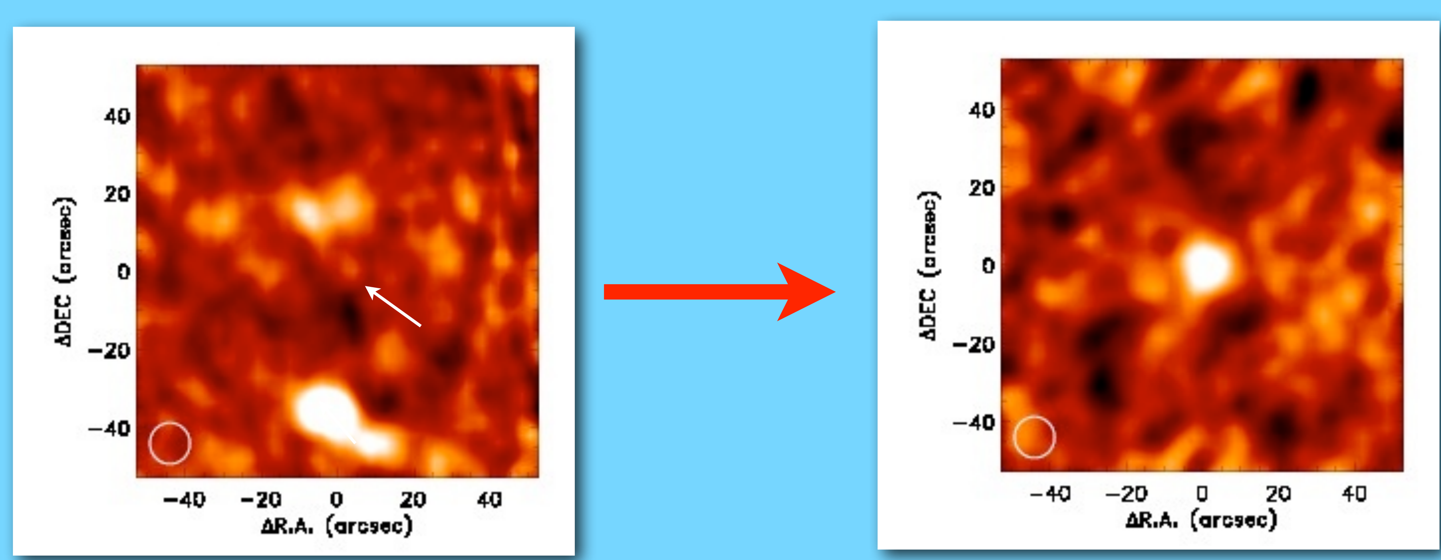
Abstract

The “TNOs are Cool!: A survey of the trans-Neptunian region” is a Herschel Open Time Key Program that aims to characterize planetary bodies at the outskirts of the Solar System using PACS and SPIRE data, mostly taken as scan-maps. The program uses a modified version of the standard PACS pipeline for basic reduction and provides special images as science products. We make use of the carefully designed observations, optimized to minimize the effect of the sky background, crucial in the detection of faint source in the far-infrared. These data reduction techniques are also utilized for other solar system targets, e.g. comets and near-Earth asteroids.

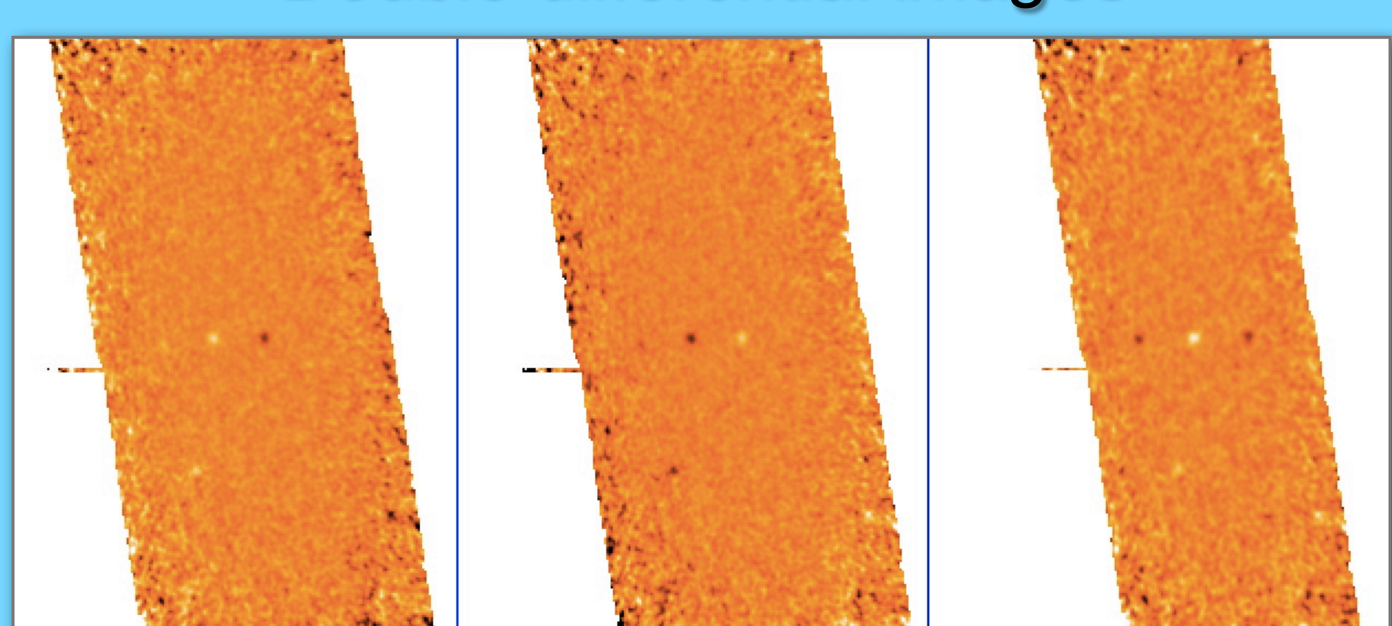
Observation strategy and data products



Demonstration of the crucial role of background elimination in the far-infrared: Original and background eliminated images of Eris at 160um. The faint blob marked by the arrow is Eris on the original image. Eris (about 6 mJy at 160um) becomes a very high signal-to-noise detection although it is close to the confusion noise level in this region

- Each target is observed at two epochs, separated in time in a way that the source moves 30-50” between the two visits in the sky, corresponding to 2.5-4 red beams.
- The images of the two visits can be used as mutual backgrounds - this setup is ideal for background elimination - this is a big advantage in the far-infrared!
- Each source is observed with both PACS filter combinations (70 or 100um and 160um) with 70 and 110 deg scan map angles (w.r.t. the detector array, ScanA and ScanB images) -- altogether 2 images in blue and green and 4 images in red, in a single visit
- **Modified version of the PACS pipeline** for basic data reduction:
  - High-pass filter width of 8, 9 and 16 (at 70, 100 and 160um, respectively)
  - Masking pixels above 2-sigma, and at the source position with 2xFWHM radius
  - Second level deglitching with nsigma=30 (MMT disabled)
- The maps obtained in Visit-1 are combined with the corresponding images of Visit-2 and together form the following 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
  - **Super-sky subtracted** images (from the co-added images, SSKY)
  - **Double differential** images (from the differential images, DDIFF) using **source matching** to determine the ideal offsets
- The **photometric uncertainty** is determined using the **implanted source method:**
  - We place 200 artificial sources on the image which have the shape of the PACS PSF in the actual band. The same type of 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 0.3 < coverage < 0.9)
  - The photometric uncertainty is the standard deviation of the distribution of the artificial source fluxes

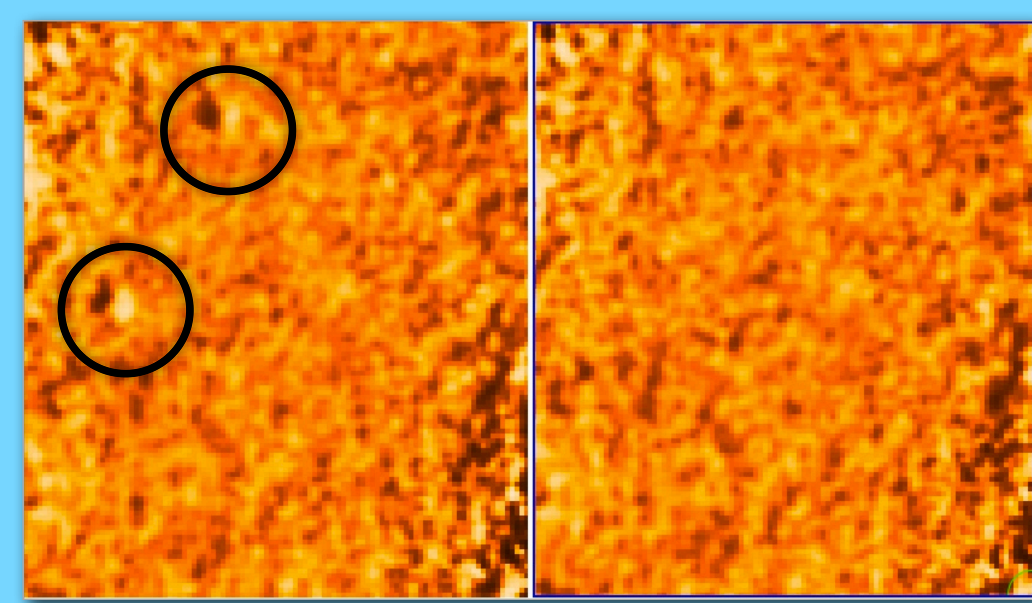
Double differential images



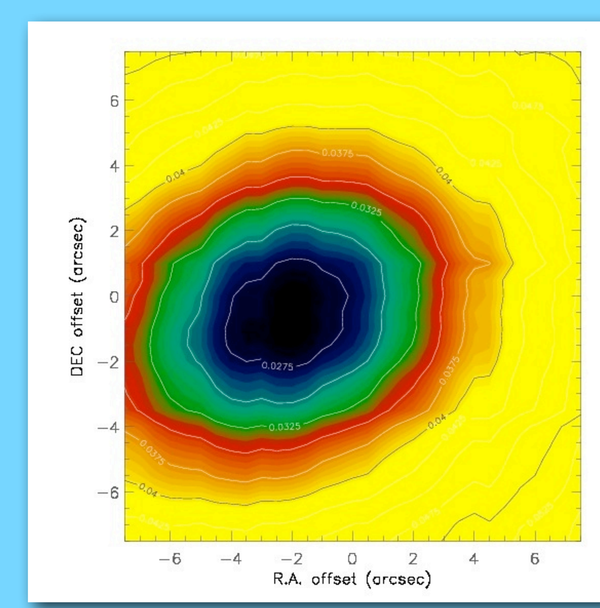
Differential, folded differential and double differential images (from left to right) of Ixion at 100um

- How to make a DDIFF image?
  - 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
  - The original and the folded/shifted DIFF images are co-added
- The DDIFF image contains a positive beam with the total flux of the target and two negative beam at the sides with “half” of the total flux
- “Side effects”: The noise is increased by a factor of √2 and flux variations between the two visits are flattened out
- Still, the signal-to-noise of the target is improved by √2 w.r.t. the DIFF image. This method has proved to provide the best performance in the detection of very faint sources (< 2mJy at 70um) superior to the DIFF or SSKY images

Background matching (on DIFF images)



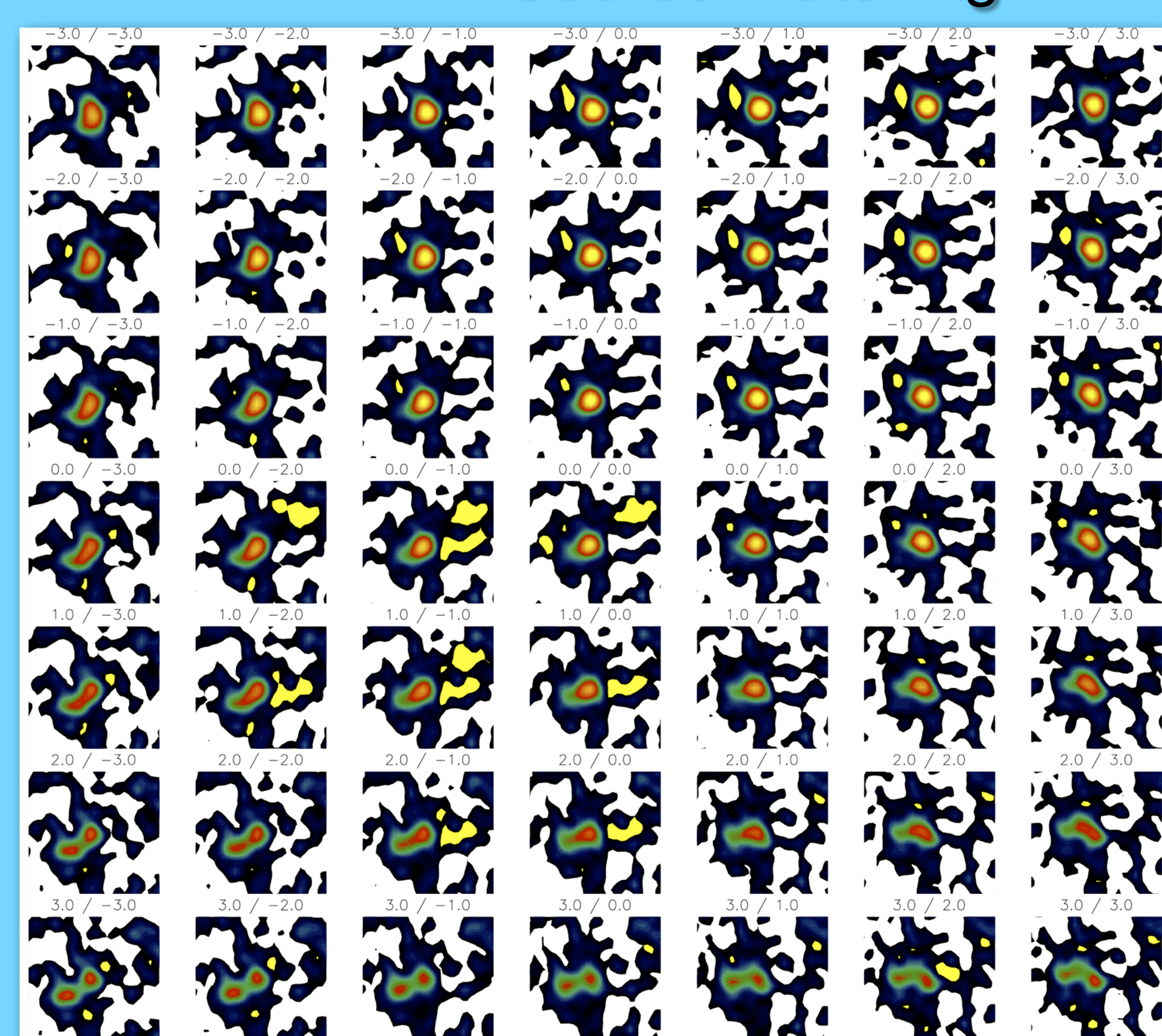
Original (left) and “background matched” (right) differential images of the same pair of 70um images



Contour map of residual noise as a function of coordinate offsets

- **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 - incorrect offset can be easily identified by the appearance of positive/negative spot pairs (see the left panel of the figure above, marked with black ovals) - these are completely eliminated on the corrected image (right panel of the same image)
- The offset to be applied can be determined using images of systematically shifted coordinate frames and then determining the offset which provides the smallest standard deviation of flux values in a pre-defined coverage interval (typically 0.3 < coverage < 0.9, see the contour map above).
- Tests prove that the same offset is obtained using all band, however, in most cases the offset can be most readily determined using the 160um images.

Source matching



Source matching for Ixion to determine the best offset for the final DDIFF image

- Background matching 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 - wrong offsets lead to distorted shapes of the target image
- **Source matching** determines the offset the original and folded DIFF images have to be shifted with to obtain the most suitable DDIFF image of the target
- Typical offset are a few arcseconds (±4” range is investigated both in R.A. and DEC)

Results

- In the TNOs are Cool! A Survey of the trans-Neptunian region Herschel Open Time Key Program we observed more than 130 targets, in total 1131 observations (1089 in “KPOT_thmuelle_1”, 2 in “AOTVAL_thmuelle_2” and 40 in “SDP_thmuelle_3”)
- A good majority of the targets (>90%) are detected in at least one band, about 50% of them are detected in all the three PACS bands.
- With our techniques we managed to reach 0.6, 0.9 and 1.6 mJy flux uncertainties using the combined products (DDIFF images) of 5-repetition single maps in the 70, 100 and 160um PACS bands, respectively.
- Our techniques are successfully applied for other moving target observed with Herschel/PACS: 1996 RQ36,1999 JU3, 2005 YU55, Apophis, etc.

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