Turnaround data in SPIRE maps

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SPIRE scan maps may optionally include the "turnaround" data taken between scan lines. This report provides instructions for how to include the turnaround data, and recommendations for usage of the turnaround data, based on theoretical considerations and on investigations into the quality of the turnaround data from scan maps taken as part of the HerMES project.

For most scientific purposes, the recommendations, in brief, are to include the turnaround data in creating the maps, but to include only data taken when the scan velocity is greater than 5 arcsec s^{-1}.

1 Introduction to turnaround data

Figure 1 shows the coverage map of one of the HerMES observations of the GOODS-South field. The left-hand panel shows the coverage including the scan lines only, while the right-hand panel shows the path with the inclusion of the "turnaround" data taken between the scan lines. Figure 2 shows the path of the central PSW bolometer for the same observation, with the turnaround data included in the right-hand panel. It can be seen that inclusion of the turnaround data can add significantly to the coverage, both in sky area (by a factor of 22%) and in depth (by a factor of 50% in observing time).

The reason turnaround data have not been included by default is that the scan speed is not constant between scans. Within the scan line, the scanning speed is constant, for example, at 30 arcsec s^{-1} for SPIRE nominal mode observations. However, at the end of the scan line, the spacecraft is slowed down to zero velocity, then slews to a new position ready to commence the next scan, once again slows to zero velocity, and then accelerates to the nominal scan velocity for the next scan.

Figure 3 shows the scan velocity and acceleration for one of the scan lines in the same observation shown in previous figures. The start and end of the nominal scan line are marked on the plot, and the data outside of that range is the turnaround data.

There are reasons not to include data taken while the spacecraft is stationary, or nearly stationary. One reason is that the large spikes in the coverage visible in Figure 1 represent very uneven coverage within a map pixel (see below and Figure 7). This could lead to poor flux estimates if there is a steep gradient within the pixel, as would be the case near a bright source. An uneven coverage map will also lead (in the HIPE naïve map maker) to a very uneven error map, which could lead to these poor estimates of the signal in the pixel being given very high weight, for example, in the HIPE SUSSEXTRACTOR source extractor. Excluding the data taken while the spacecraft is moving at very low velocity leads to a more even coverage, as shown below.

One of the reasons for adopting a scan map approach to SPIRE observations, rather than using point-and-stare observations, is the presence of $1/f$ noise. This is noise, coming from various instrumental effects, that scales approximates inversely with frequency, such that there is significant correlated noise at low-frequencies. The so-called "$1/f$ knee" in the power spectrum is the frequency below which $1/f$ noise is significant. For SPIRE, depending on the method used to remove temperature drifts, this can be below 4 mHz (Pascale et al., 2011), but might otherwise be around 20 mHz.[1]

The spatial scale above which the $1/f$ noise might produce effects in the maps is a function of the scan speed and the $1/f$ knee frequency:

$$\text{spatial scale} = \frac{\text{scan speed}}{1/f \text{ knee frequency}}$$

For example, if the scan speed is 30 arcsec s^{-1}, and the $1/f$ knee frequency is 20 mHz, then the $1/f$ noise could potentially produce features in the map on a spatial scale of 1500 arcsec (25 arcmin). Or if the scan speed is 5 arcsec s^{-1}, the $1/f$ noise would not affect scales smaller than 250 arcsec.

As can be seen from Figure 3, the spacecraft pauses at the start and end of each scan, and this pause may last several seconds. Inclusion of data taken while the spacecraft is stationary may lead to unwanted noise effects at those positions. For this reason, and because of the $1/f$ noise, it is recommended that if turnaround data are included, a minimum velocity should be specified, and a minimum velocity of 5 arcsec s^{-1} would keep the majority of $1/f$ noise effects on scales that are sufficiently large for most astronomical purposes.

Exclusion of some of the turnaround data may lead to gaps in the maps. However, the velocity cut of 5 arcsec s^{-1} is sufficiently inclusive to avoid this, for the default map pixel size of 6 arcsec (PSW).

[1] See presentation by Kevin Xu to the SPIRE Data Analysis Group (SDAG), 19 Nov 2009

Figure 3 shows the acceleration, which is typically 5.5 arcsec s^{-2} when the spacecraft is accelerating. If a minimum velocity is set at 5 arcsec s^{-1}, then while the spacecraft is accelerating between zero velocity and 5 arcsec s^{-1}, this will leave a gap in coverage of $v^2/2a = 2.3$ arcsec, which is less than half of a default PSW map pixel (6 arcsec).

Figure 4 shows the coverage as in Figure 1, but with the data excluded when the scan velocity is less than 5 arcsec s^{-1}. No gaps have been introduced by imposing this cut, and the sharp peaks in coverage when the spacecraft is stationary, evident in Figure 1, have been reduced. The increase in coverage area is now 20% while the increase in observing time is now 35%.

So far only PSW has been considered. For PMW and PLW, the default map pixel size is larger, so the inhomogeneities in coverage will be less pronounced than for PSW.

2 How to include turnaround data

The instructions here are provisional, awaiting implementation of certain changes to the mapper code in HIPE.

To include turnaround data, first it is necessary to call `extend=True` in the call to `cutPhotDetTimelines` in the pipeline script:

```
psp = cutPhotDetTimelines(psp, extend=True)
```

Turnaround data will then be included in the Level-1 data.

If using the `naiveScanMapper` to create Level-2 data, by default all data taken when the spacecraft is moving faster than 5 arcsec s^{-1} will be included. However, it is possible to specify non-default velocity limits in the call to the mapper, using the optional parameters `minVel` and `maxVel`. For example, to use only data taken with velocity between 0 and 31 arcsec s^{-1}, the call would be as follows:

```
mapPsw = naiveScanMapper(scans, array="PSW", minVel=0, maxVel=31)
```

3 Tests of the quality of turnaround data

In order to test the quality of the turnaround data, we took 8 of the 76 observations taken in the GOODS-South field as part of the HerMES project. These observations are offset from each other ("dithering"), in order to produce a more uniform coverage when the observations are combined.

3.1 Signal in map pixels

We created maps from these 8 observations combined, first using only the scan data, and then using only the turnaround data, with or without limits imposed on the velocity of the spacecraft. Then, in order to compare these maps, we selected those pixels with coverage in both maps, and compared the data at those pixels.

Figure 5 shows the signal in each of those pixels (excluding low coverage) from the scan data and the turnaround data. The symmetry of the plot suggests no serious problems with the turnaround data.

If the turnaround data are significantly worse, this might be expected to show up in a larger scatter of the bolometer samples within the pixel. This is calculated from the error and coverage maps: the scatter in the bolometer samples is equal to the value of the error map, multiplied by the square root of the coverage. (This is because the error map from the HIPE naïve map maker is the standard error on the mean of the bolometer samples falling within that pixel.)

Table 1 shows the median scatter in the signal measured by the bolometer samples within a pixel. There is no evidence from this that the turnaround data are worse than the scan data, even for very low velocities. However, in the case of strong drifts or significant $1/f$ noise, the data might be of a lower quality for slower scanning velocities. If anything, there may be marginal evidence for a smaller scatter at lower scan velocities. If so, this could be because of an uneven distribution of the samples within the pixel: see below and Section 1.

3.2 Measured fluxes of point sources

We created maps using the scan data, as above, and using the scan and turnaround data combined, with and without a velocity cut to exclude data taken while the spacecraft was moving slower than $5\,\mathrm{arcsec\,s^{-1}}$. Source extraction was then performed on those maps using SUSSEXTRACTOR in HIPE, and using only those pixels with at least 20 samples of scan data and 20 samples of turnaround data, as above.

Figure 6 shows the offset in flux resulting from the inclusion of turnaround data. On average, the turnaround data leads to a lower estimate of the source flux density.

For all (or for $v > 5\,\mathrm{arcsec\,s^{-1}}$) turnaround data, the mean linear offset in flux for PSW is $-1.8\,\mathrm{mJy}$ ($-1.1\,\mathrm{mJy}$), or $-0.03\,\mathrm{dex}$ ($-0.02\,\mathrm{dex}$) in log(flux); for PMW it is $-2.6\,\mathrm{mJy}$ ($-1.9\,\mathrm{mJy}$), or $-0.03\,\mathrm{dex}$ ($-0.03\,\mathrm{dex}$) in log(flux); and for PLW it is $-2.5\,\mathrm{mJy}$ ($-2.4\,\mathrm{mJy}$), or $-0.03\,\mathrm{dex}$ ($-0.03\,\mathrm{dex}$) in log(flux).

Figure 7 shows the location of the bolometer samples in the 3×3 pixels at the locations the five brightest sources shown in Figure 6 for PSW. It can be seen that including all of the turnaround data leads to some sharp peaks in coverage, and inhomogeneities of coverage within the pixel.

Causes for the offset could be a combination of (1) the uneven distribution of samples within the pixel, leading (see below) to a bias towards lower fluxes as a consequence of the algorithm used in SUSSEXTRACTOR, (2) baseline removal effects (a split median baseline removal was used), or (3) a random effect, due to a small sample. However, even if the offset is real, it is small, and likely to be negligible for most scientific purposes.

An explanation for (1) could be that the centre of the PSF is approximately Gaussian, and the second derivative of a Gaussian function is positive further than σ from the centre of the Gaussian (where $\sigma = 0.42 \times \mathrm{FWHM}$, for example, approximately 7.7 arcsec for PSW). In pixels where the second derivative (i.e., the Laplacian) is positive, a larger region of the pixel lies below the mean value for that pixel than above the mean value. So an inhomogeneity within the pixel is more likely to lead to a lower measured value than a higher measured value. SUSSEXTRACTOR generally uses 5×5 pixels to estimate the flux, so most of the pixels used in the flux estimate are in regions of the PSF with a positive Laplacian (the pixel size is approximately FWHM/3). Combined with the increased weight given to a pixel with a higher coverage, this means that inhomogeneous coverage is likely to lead to a lower flux estimate with SUSSEXTRACTOR.

4 Conclusions

We have examined the quality of the turnaround data in some SPIRE observations and found no cause for concern about data taken between scans in SPIRE observations. However, there can be undesirable effects on subsequent analysis if there are sharp peaks of coverage in particular map pixels, or in particular regions of map pixels, as has been shown with the example of flux densities derived from SUSSEXTRACTOR. For this reason we recommend (for default settings) not including turnaround data taken when the telescope is scanning with a velocity less than $5\,\mathrm{arcsec\,s^{-1}}$.

References

Pascale, E., Auld, R., Dariush, A., Dunne, L., Eales, S., Maddox, S., Panuzzo, P., Pohlen, M., Smith, D. J. B., Buttiglione, S., Cava, A., Clements, D. L., Cooray, A., Dye, S., de Zotti, G., Fritz, J., Hopwood, R., Ibar, E., Ivison, R. J., Jarvis, M. J., Leeuw, L., López-Caniego, M., Rigby, E., Rodighiero, G., Scott, D., Smith, M. W. L., Temi, P., Vaccari, M., and Valtchanov, I. (2011). The first release of data from the Herschel ATLAS: the SPIRE images. *MNRAS*, 415:911–917, 1010.5782.

Table 1: Median scatter in the signal measured by bolometer samples within a pixel, for different velocity ranges in turnaround data. For PSW (top), PMW (middle) and PLW (bottom).

Turnaround velocity limits	No. of pixels	Scan: med. RMS (Jy)	Turnaround: med. RMS (Jy)
No limits	75245	0.0389	0.0386
$v < 5\,\text{arcsec/s}$	19952	0.0386	0.0376
$v < 1\,\text{arcsec/s}$	15940	0.0386	0.0374
$v < 0.1\,\text{arcsec/s}$	6306	0.0388	0.0361

Turnaround velocity limits	No. of pixels	Scan: med. RMS (Jy)	Turnaround: med. RMS (Jy)
No limits	29037	0.0413	0.0411
$v < 5\,\text{arcsec/s}$	9382	0.0413	0.0405
$v < 1\,\text{arcsec/s}$	8105	0.0414	0.0403
$v < 0.1\,\text{arcsec/s}$	3713	0.0415	0.0386

Turnaround velocity limits	No. of pixels	Scan: med. RMS (Jy)	Turnaround: med. RMS (Jy)
No limits	14416	0.0488	0.0482
$v < 5\,\text{arcsec/s}$	4632	0.0486	0.0474
$v < 1\,\text{arcsec/s}$	4094	0.0485	0.0472
$v < 0.1\,\text{arcsec/s}$	1962	0.0488	0.0449

Figure 1: Coverage from one of the HerMES GOODS-South observations (PSW), with turnaround data included in the right-hand image. The intensity is plotted on a logarithmic scale, peaking at 251 bolometer samples in a pixel, which is the highest coverage in the map including turnaround data. For comparison, the highest coverage in the map without turnaround data included is 31 bolometer samples in a pixel. Including the turnaround data increases the total area covered by 22%, from 1083 arcmin^2 to 1322 arcmin^2, and the total observing time by 50%, from 65 169 s to 98 266 s.

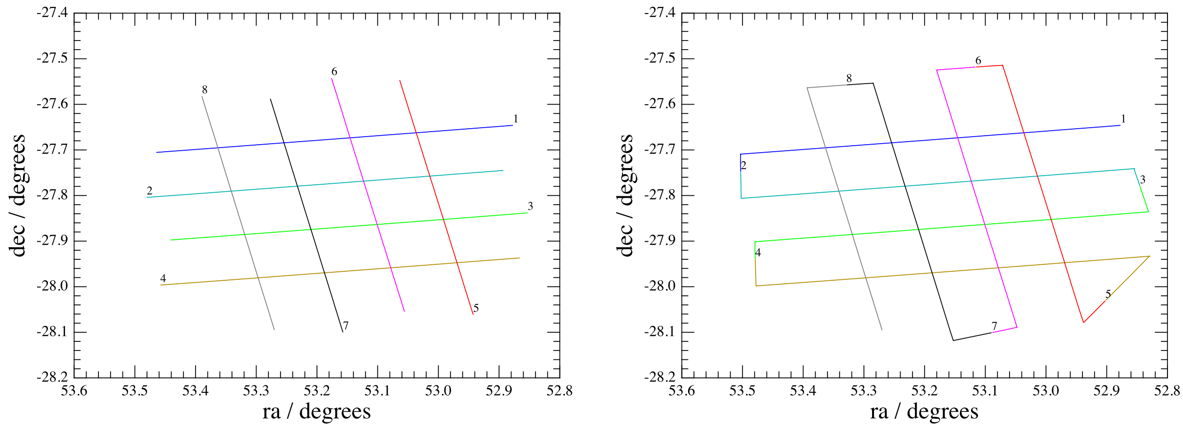

Figure 2: Path of the central PSW bolometer (PSWE8) for the same observation as in Figure 1. The left-hand plot shows the path of this bolometer excluding turnaround data, and the right-hand plot includes the turnaround data. The start of each scan line is marked with 1 … 8.

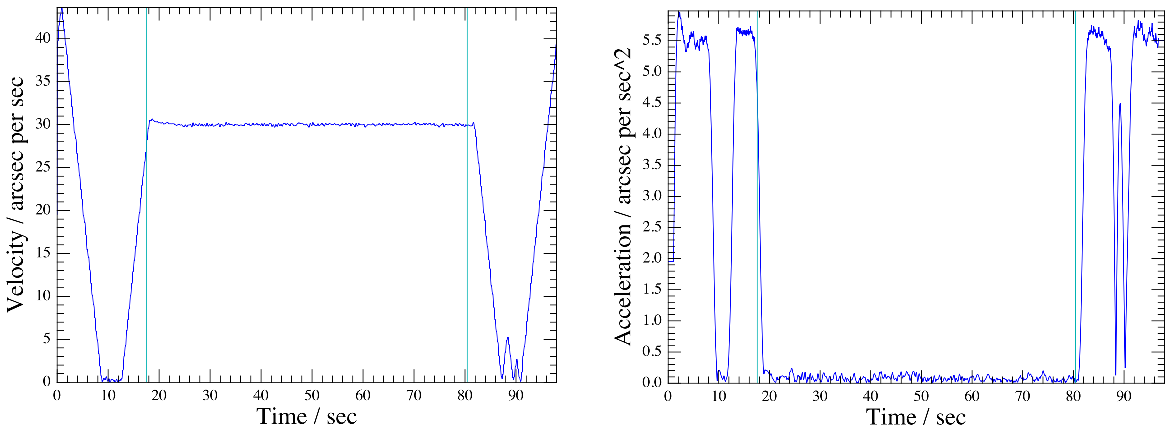

Figure 3: The velocity (left) and acceleration (right) during the second scan line of the GOODS-South observation. The velocity at each sample time is calculated from the ra and dec of the adjacent samples. For the acceleration, in order to give a smooth plot, the acceleration at a particular sample time is estimated from the ra and dec at that sample time, and 20 samples before and 20 samples after that sample time (the sampling rate is 18.6 Hz). The vertical lines mark the start and end of the nominal scan line, as given by the “startNominalScanLine” and “endNominalScanLine” meta-data entries in the product within the Level-1 context.

Figure 4: As Figure 1, but excluding turnaround data taken when the scan velocity is less than 5 arcsec s^{-1}. The maximum coverage in the map including turnaround data is now 50 bolometer samples per pixel. Including the turnaround data in this case increases the total area covered by 20% (previously 22%), from 1083 $arcmin^2$ to 1320 $arcmin^2$, and the total observing time by 35% (previously 50%), from 65 169 s to 87 701 s.

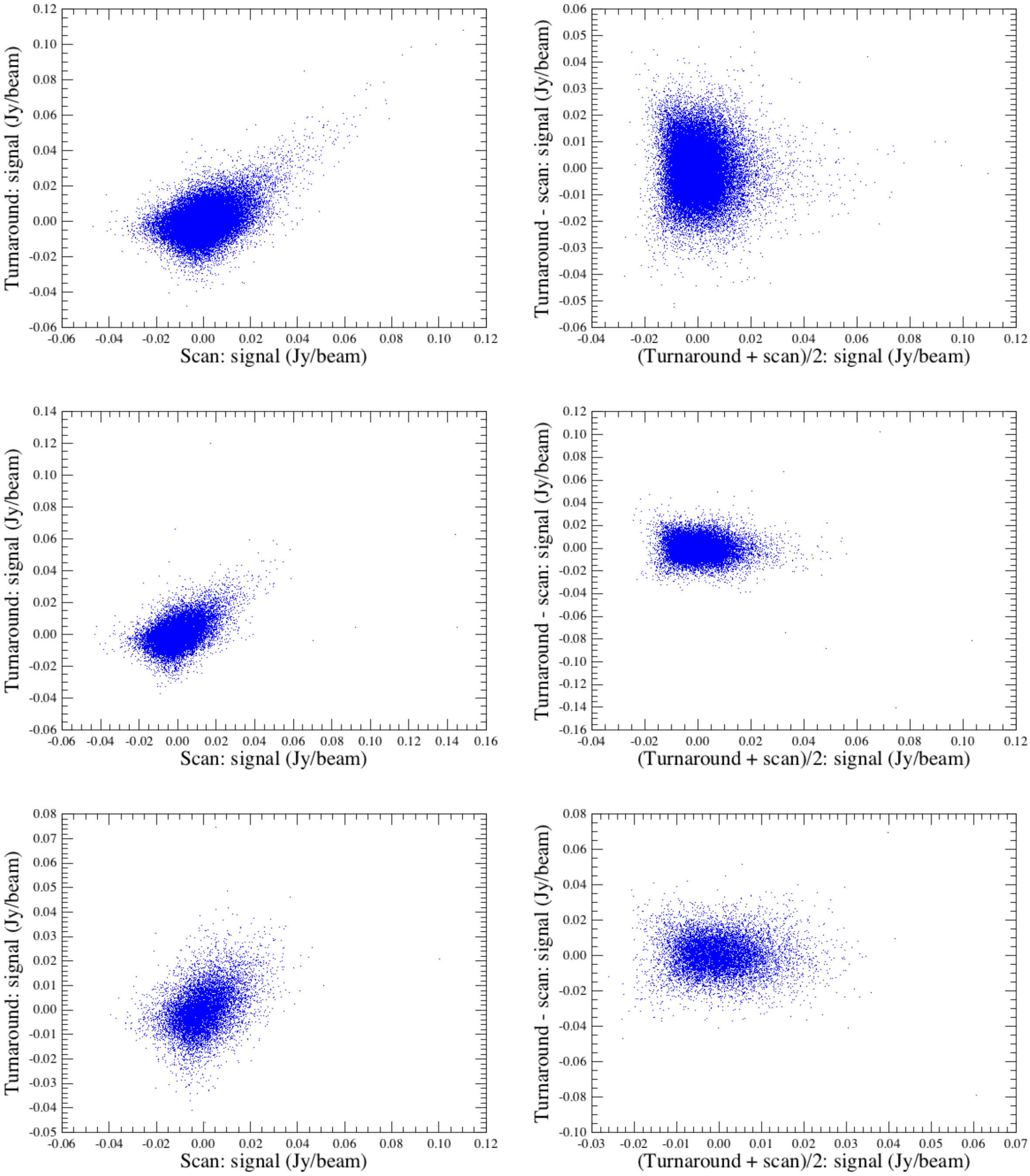

Figure 5: Measured signal in the pixels in common between the scan data and the turnaround data, for the pixels with more than 20 bolometer samples in each of the scan data map and the turnaround data map. This corresponds to 50899 of the 75245 pixels in common for PSW, 23495 of 29037 for PMW, and 11464 of 14416 for PLW. The mean offset for (PSW, PMW, PLW) is $(-0.08, 0.01, 0.34)$ mJy/beam. The uppermost plots are for PSW, middle for PMW and bottom for PLW.

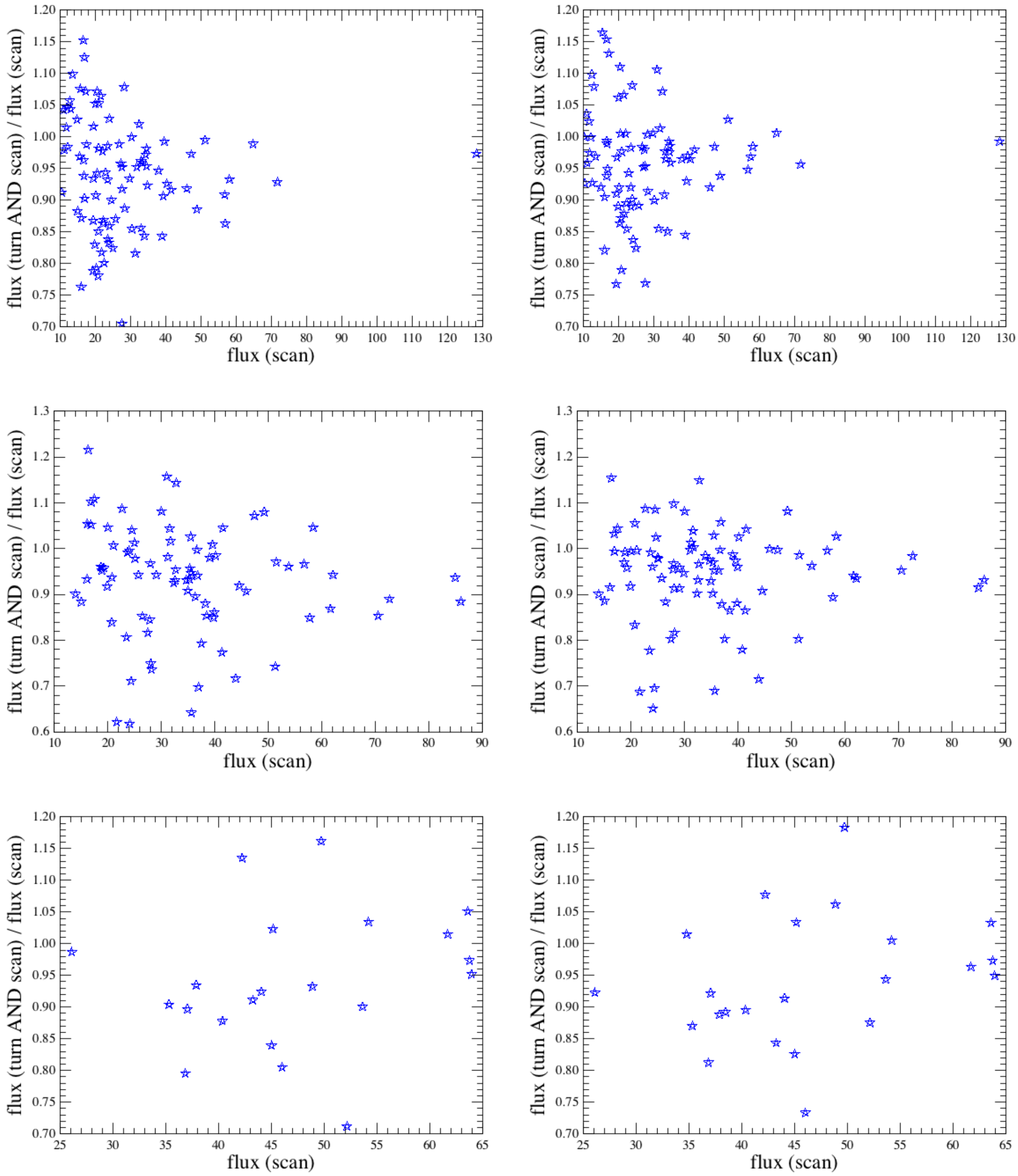

Figure 6: Ratio of source fluxes including and excluding the turnaround data, for all turnaround data (left), and for only the data taken when the spacecraft had a velocity greater than 5 arcsec s^{-1} (right). Top plots are for PSW, middle for PMW and bottom for PLW.

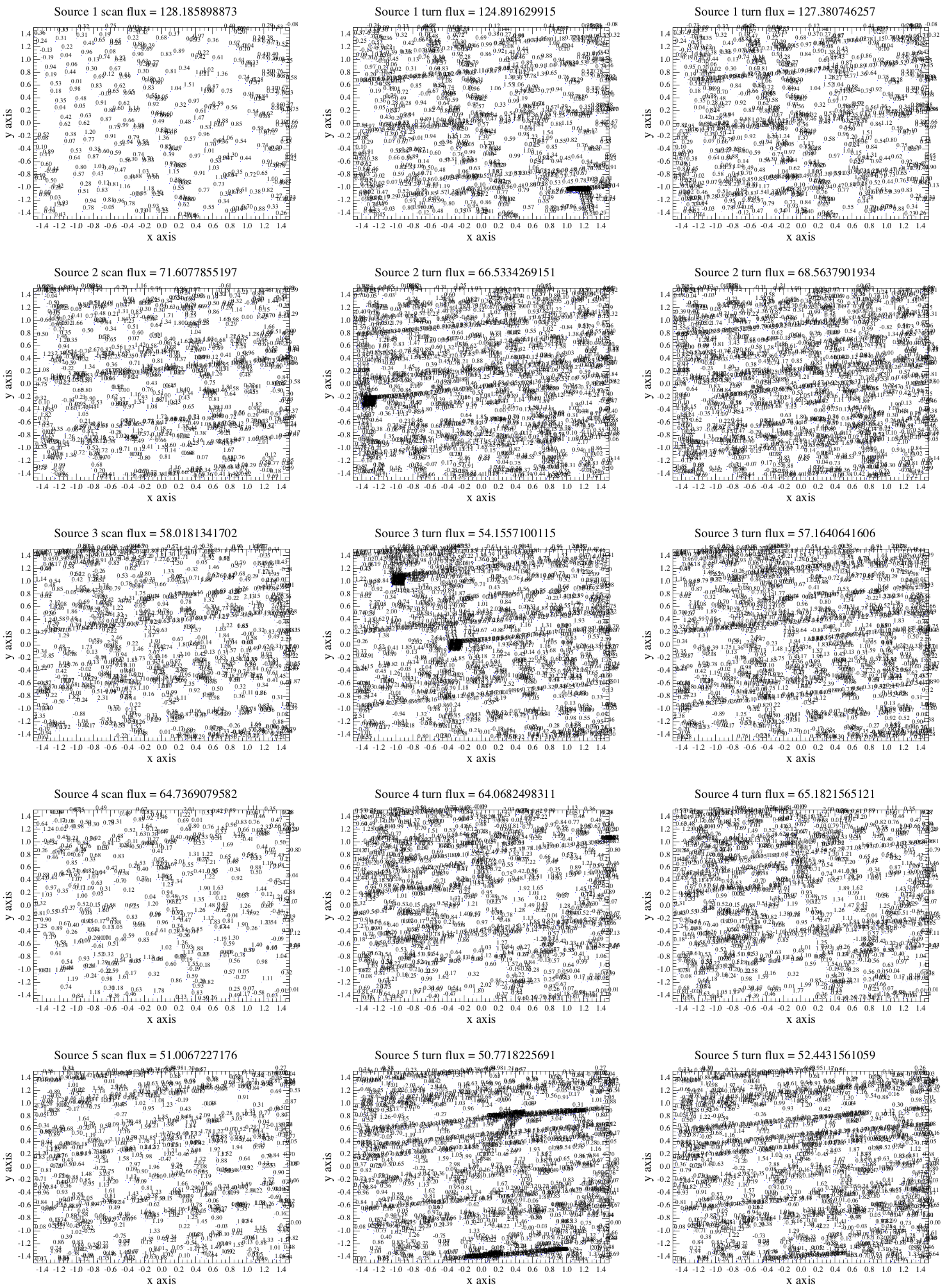

Figure 7: The bolometer samples contributing to the central 3×3 pixels of the five brightest sources in Figure 6 for PSW. in the title of each plot is the SUSSEXTRACTOR flux in mJy. The axes are pixel coordinates in the ra (x) and dec (y) directions, with $(0, 0)$ at the centre of the pixel in which the source centre lies. The tiny dots are the locations of the samples and the numbers are the intensity of the sample, divided by the measured flux. Each row is one source: the left-hand plot shows the scan data only, the middle plot includes all of the turnaround data, and the right-hand plot includes only the turnaround data with $v > 5\,\mathrm{arcsec\,s^{-1}}$. Although most of the numbers are illegible, the sharp clusters of points are clearly visible when all of the turnaround data are included (central column).