Pointing Reconstruction in HIFI Observations

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This note describes changes in the HIFI pipeline processing and quality flagging with the new approach to pointing reconstruction starting in HIPE 13[1]. The context is for Users of the Herschel Science Archive, to be informed where the estimated quality of the pointing reconstruction can affect scientific interpretations of observations of semi-extended or compact sources.

1. Pointing reconstruction in the Standard Product Generation pipeline

The pointing history is calculated on an Observational Day (OD) basis and formatted into products for each observation as part of Standard Product Generation (SPG) at ESAC. Over the time range (in UTC) of every obsid, an Attitude History File (AHF) and a Pointing Product extracted from the OD-based products are provided as data products for each observation in the Auxiliary product tree under the Observation Context. The Pointing Product in particular provides the usable timeline of attitudes, in the frame of the spacecraft's Attitude Control Axis (ACA) in which the x-axis is the telescope boresight. A schematic description of the telescope's attitude control system can be found in the Herschel Observer's Manual[1].

1.1 The new pointing reconstruction approach

Starting in HIPE 13, the calculation of the pointing history includes a new method[2] to estimate the drift on the four gyroscopes more accurately (in short hand the gyro-based method), leading to a higher fidelity representation of the short-term pointing stability or so-called "jitter" of the telescope. This is quoted as the Relative Pointing Error (RPE). The method was developed and introduced into HIPE by the PACS ICC[3].

The RPE is measured from integrations on a target at a fixed position, between telescope moves. The RPE is quoted to have a requirement of 0.3 arcsec (1-σ) when measured over 60 sec. To HIFI with beam sizes between ~11 and 43 arcsec HPBW, this quantity may seem inconsequential. However the improved characterization of the drift on the gyros also provides lower reconstructed attitude errors, cast in terms of the Attitude Measurement Error (AME), in general. This can be viewed as a reduction to the error of the reconstructed path of the telescope, whether stationary or making short slews or continuous scanning motion during an observation.

1.2 Benefits to HIFI

The HSC is in progress to exploit the reduced AME to revise estimates of certain telescope pointing performance metrics (such as the absolute pointing error) and the

[1] http://herschel.esac.esa.int/Docs/Herschel/html/ch02s04.html
[2] http://herschel.esac.esa.int/twiki/bin/view/Public/ImprovedPointingGyro
[3] A PACS ICC technical note PICC-ME-TN-042 (H. Feuchtgruber, Sep. 2012) describes the approach, interested readers should contact the HSC helpdesk. See also http://herschel.esac.esa.int/CalibrationWorkshop5/Presentations/27March/1515_Feuchtgruber.pdf

telescope PSF using observations of celestial targets acquired by PACS for pointing calibrations. The applied benefits of the reduced AME to HIFI observations can be significant:

- In Point AOT observations, at a fixed LO frequency and fixed target position, the indicated offset from the intended position and spread of Level 2 dataset positions *before averaging* will give an indication of the extent of coupling losses if the RMS of reconstructed positions is at least 20% of the beam size and the emitting/absorbing source is compact. Observations using position switch mode (including load chop or frequency switching with a sky reference) as in the example below would typically have a larger spread around the intended position due to slews greater than a few arcmin angular distance to/from the reference position, compared to DBS raster which uses 3 arcmin nods of the telescope.

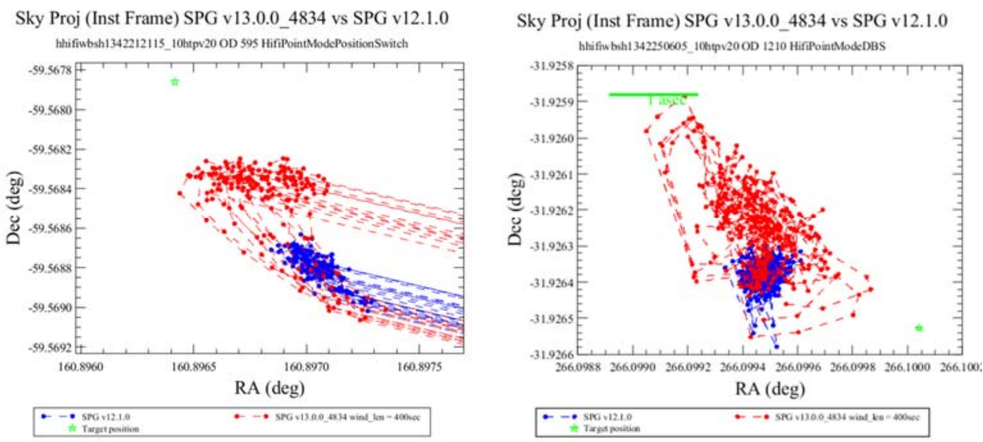

Figure 1: Examples of Point AOT observations using position switching (left) and dual beam switching (right). Blue points are from HIPE 12 pointing reconstruction, red points are from the gyro-based method in HIPE 13. The points represent positions where ON-target spectrum datasets have been obtained; they are averaged to a single dataset in the HIFI pipeline at Level 2.

- In Spectral Scan AOT observations, in which integrations are taken at multiple LO settings, the indicated spread of Level 2 datasets around the intended position will similarly give an indication of beam coupling losses at different frequencies (since only multiple integrations at the same LO frequency are averaged together in the pipeline as in Point AOT observations). This would be important to check when comparing spectral line intensities.

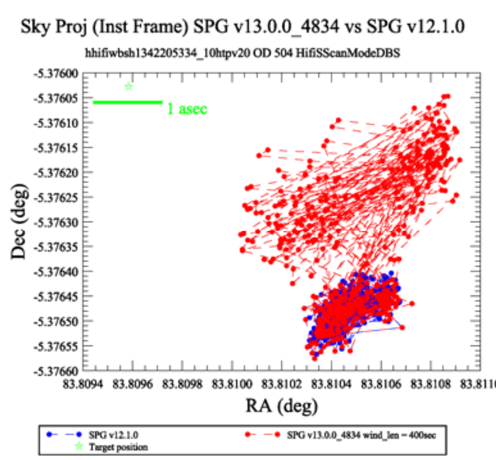

Figure 2: Example of a Spectral Scan observation using dual beam switching. Symbols are as in Figure 1. In this plot, each point may represent a different LO frequency.

- In Spectral Mapping observations, taken as either a DBS raster or an OTF map, the improved accuracy of the pointing reconstruction provides a more accurate construction of the spectral cubes in which the convolved signal is weighted by map readout position. In fact this is especially important for OTF maps in which it was recognized early in the development and application of the gyro-based method (in collaboration with the PACS ICC), that the line scan pointing mode performed anomalously on the telescope, deviating from the intended scan path by up to ~3 arcsec after each interlaced excursion to/from a sky reference position (see the example below). This was the so-called “zig-zag” problem which produced significant pattern noise in data obtained on compact or resolvable structures (particularly in Band 7). This erroneous motion is only recognized but not understood, and in the pipeline through HIPE 12 the pattern noise was caused by a complete lack of representation of the anomalous pointing (thus causing improper signal weighting) prior to introduction of the gyro-based method.

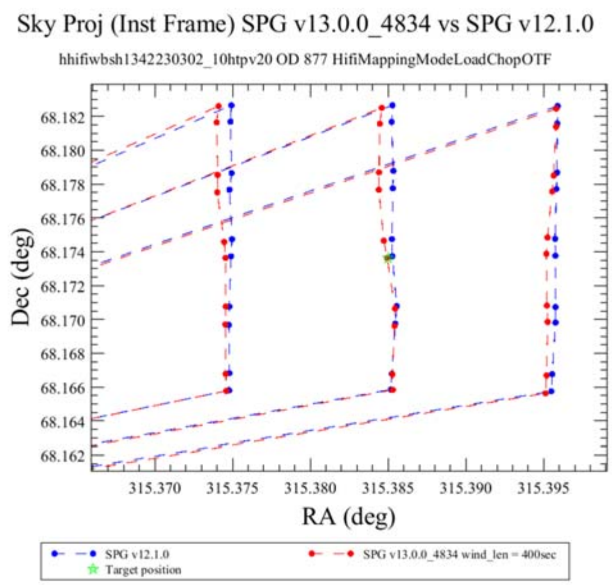

Figure 3: Example of an OTF map using internal load chop and position switching to a sky reference. The positions from HIPE 12 pointing reconstruction (blue) closely follows the intended path, whereas the gyro-based pointing (red) reveals anomalous path deviations in the line scan mode.

1.3 Limitations on the Pointing Reconstruction and Quality Flagging

Still in context with basic processing in the SPG (independent of instrument), there are some limitations to the pointing reconstruction accuracies which are anticipated from several possible contributing sources of error. The most important one relates to the quality of attitude solutions derived from star tracker telemetry, which the gyro-based method is designed to refine. The quality of properties of cataloged guide stars available to the star tracker during an observation translates directly to the quality of the star tracker output attitude solutions, and if the star tracker solution has a lower quality due to one or more guide stars with a quality issue (such as photometric uncertainty or variability, crowded region, etc), then the final pointing reconstruction using the gyro-based method will also have a low quality. This can result in suspiciously large spread around the intended pointing, giving very poor impressions of the relative stability of the telescope.

In this way, the gyro-based method, which is not the source of the problem, is the canary in the coal mine when the jitter component becomes unrealistically large and unreliable (see the example below), revealing pre-existing and untreated problems at the level of star tracker data processing.

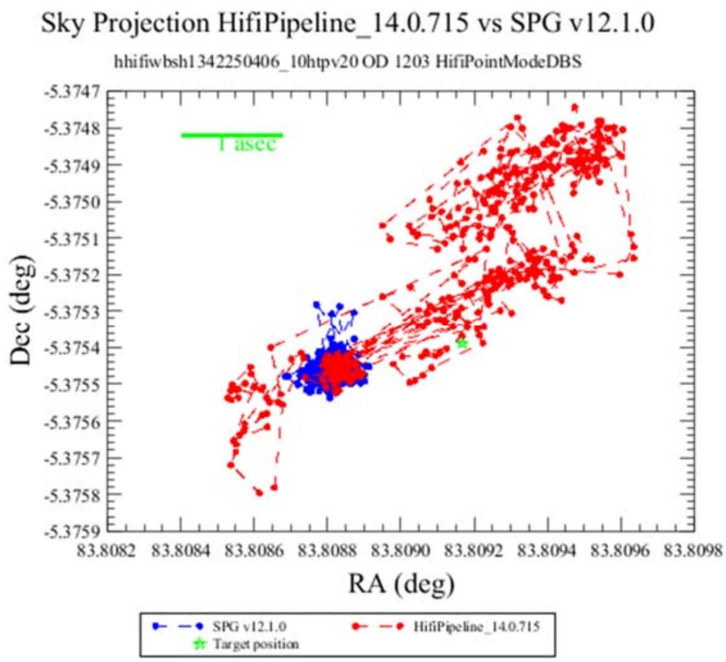

Figure 4: Example of an observation with poor apparent pointing stability. The pointing reconstruction for this observation is affected by guide star quality issues, and results in very low probabilities of good fits to the sensor data on each spacecraft axis, producing an unreliable short-term stability component.

There can be other reasons for lower quality attitude solutions, such as the availability of less than 9 nominally-required guide stars for some regions of the sky. The gyro-based method also makes an assumption on the drift rate of the gyros, that it is linear over a specified time interval, this may not always hold (although at this time there is insufficient testing on this point). Other possible sources of error in the pointing system are described by Sanchez-Portal et al. (2014 ExA 37, 453). The most notable of these which is not reflected in the pointing reconstruction in any way is the distorting thermos-elastic effects on the star tracker in certain orientation angles with respect to the sun.

Testing shows that the frequency of compromised pointing reconstruction is fairly high, 20-30% of observations (all instruments) sampled randomly across the sky. For this reason, a quality flag has been introduced into the Pointing Products. The flag has a value between 0.0 (worst) and 1.0 (best), and is based on goodness of fit statistics (or more correctly, the probability of a good fit to the sensor data on each spacecraft axis) produced during processing in the SPG. The flag takes into account the dynamic nature of the pointing system in which the availability of gyro-based fitting solutions during an observation has to be above a certain threshold, since the actual pointing reconstruction may be composed of both the gyro-based method and so-called "simple" pointing reconstruction (as in pre-HIPE 13) using standard onboard Kalmann filtering over ranges when data for the refining the jitter component are unavailable.

At the level of Pointing Product generation, the flag is informational and is not specific to any instrument, nor have any observing mode or celestial source type dependencies; it strictly reflects pointing reconstruction quality over the time range of the observation but otherwise independent of the instrument or the observing mode in operation. The quality flag *is* more directly depending on region of sky where the telescope was pointed, i.e. where guide star "bogies" may have entered among the set used, and/or at least 9 nominal quality guide stars were not available to the star tracker. Lower quality results occur where we might expect such guide star problems, e.g. towards the Galactic Center, the Orion Molecular Cloud, Carina, or any field of view in the generally complex Galactic Plane. Note that the star tracker field of view is along the –x axis (opposite that of the instrument payload). The frequency of problematic tracking of solar system objects related to guide star quality is not known, except to say that planet observations are also affected, and cases have been identified with exceptionally low reliability pointing. A more complete survey of problematic regions will be carried out after the public release of HIPE 13.

2. Processing in the HIFI pipeline

The doPointing[4] task in the HIFI Level 0 pipeline processes the Pointing Product with each obsid, temporally resampling and assigning attitudes to the spectrum datasets in the appropriate instrument frame (mixer beam), including those taken on sky reference positions and internally. By default the attitudes are taken from the "official" pointing which in HIPE 13 means the gyro-based attitudes. Due to the quality issues described above, the HIFI pipeline includes four new steps, which are:

1. Read the Pointing Product quality flag and copy this to the HIFI Obs Context header, for information.
2. Raise a "suspicious pointing flag" which is a simple True/False Boolean, and set to True when the Pointing Product quality flag is below a certain threshold (around 0.8), and copy this to the Obs Context and HIFI timeline products. This flag will also appear in the Quality Summary table produced at the end of the pipeline.
3. Revert to "simple" pointing reconstruction provided in the Pointing Products in addition to the gyro-based pointing, when the quality flag is below a cutoff value of 0.4. This basically amounts to reading a different quaternion column from the default.
4. The Pointing Product column which was applied to the HIFI data is reported as a metadatum in the Obs Context and HIFI timeline products.

The pipeline also compares the intended position as entered by the original observer in HSpot to an average of positions of all Level 2 spectrum datasets filtered down to only the ON position (i.e., excluding sky reference and internal calibration spectra). When the difference is more than 3 times the Absolute Pointing Error (APE), an "anomalous pointing" flag is raised and reported as a ratio in the Obs Context and in the Quality Summary product. The APE has different values at different phases of the mission (see e.g. Sanchez-Portal et al. 2014), and is stored in the HIFI calibration tree.

The reason for Step #3 is that when the Pointing Product quality flag based on tabulated goodness of fit statistics is low, the impressions of pointing stability can be exceptionally poor. This results in unreliable spectral cube construction, or the

[4] http://herschel.esac.esa.int/hcss-doc-13.0/load/hifi_pipeline/html/dopointing.html

potential for misinterpretations of pointing-related coupling losses at a fixed position. While the simple pointing is also not any more reliable and may involve slightly higher systematic offsets from the intended position, it does not contain the misleading stability component, and therefore it is chosen to be the least misleading in cases where the attitude solution is compromised by, e.g., guide star quality issues. *It must be emphasized that the affected observations do not have reliable relative positional accuracies in either version of the pointing reconstruction. For these observations, the only quantity which is worthy of attention is the anomalous pointing flag raised by the pipeline when the average position of all ON-source spectra differs from the intended target position by more than 3*APE.*

3. Recommendations to the Herschel Science Archive User

If the HIFI observations of interest have been taken in Bands 1 or 2, then nothing needs to be done, except to note whether the anomalous pointing flag has been raised to indicate a systematic offset of the observation by more than 3 times the prevailing APE. This can indicate either a real pointing problem, or an error in the attitude reconstruction. For a compact source a real pointing offset more than a few times the APE would be noticed in these bands as an obvious degradation in S/N ratios in the targeted spectral lines.

For observations in Bands 3 through 7 with decreasing values of the HPBW, the relative pointing performance becomes meaningful on sources which have emitting or absorbing structures smaller than the beam, down to a resolving limit of around 10% the beam size at high S/N ratios. In these cases, the User must regard with a high degree of suspicion any observation which has a value of the "gyroAttQuality" flag less than 0.4, which is sufficiently poor that the gyro-based pointing has been avoided in the pipeline and the "simpleFilterQuat" value appears with the "attitudeQuaternion" keyword in the Obs Context. All interpretations based on relative astrometry may be unreliable to any quantifiable level.

For observations in Bands 3 through 7 which have the "gyroAttSuspicious" flag set to True and the gyroAttQuality ≥ 0.4, then the gyro-based pointing has been applied but the User should use caution when interpreting weird line ratios in compact or semi-extended structures, attributing these to pointing-related coupling losses at the different LO frequencies.

For all other observations, with either no pointing quality issues or the celestial source fills the beam, there are no caveats.

As a visualization aid, the User may use the PlotObservationPointings.py available in HIPE 13 under the HIFI Useful Scripts menu.

4. Relation to the bulk pointing performance parameters

Quoting pointing performances of the telescope in terms of the APE, RPE, and other bulk quantities derived statistically is often appropriate when publishing scientific results. The bulk performance parameters for *Herschel* are found on the HSC's pages[1] and in the journal paper by Sanchez-Portal et al. (2014). These are based on analysis of pointing calibration observations processed through HIPE 12, so not yet incorporating the gyro-based method for pointing reconstruction at this writing.

However, regardless of the attitude reconstruction method, there are some important facts about the pointing system performances which are not reflected in the bulk characterizations.

First, they are derived from PACS observations of point sources selected for pointing calibrations[5], generally unresolved stellar sources located in well-behaved regions (in terms of guide star fields). A survey of the Pointing Product quality flags shows that there are very few if any problems in pointing reconstruction quality for these observations, ruling out guide star quality issues. Since these observations are the basis of performance studies of the telescope pointing, and the targets have been returned to a number of times, there is a strong weighting towards data from well behaved parts of the sky, and the results published by Sanchez-Portal et al. (2014) represent the most ideal performance of the pointing system. Results are not reflected where a significant amount of *Herschel* science observing time has been invested. This fact was recognized during testing with the high frequency of low quality attitude solutions. Similarly, the mode of observing used to acquire the pointing calibration data was almost entirely restricted to the PACS chopped point source mode, and the descriptions by Sanchez-Portal et al. lack references to behavior in other observing or pointing modes as part of a general summary of the full pointing system performance where they are significant to science, for example the anomalous line scanning in HIFI OTF maps.

The User is advised to regard currently published bulk performance parameters and descriptions to reflect when the telescope pointing system is on its best behavior, and most suited to PACS point source photometric observations in well behaved regions of the sky; significant deviations in performances and degraded pointing reconstruction quality will occur in regions with sub-nominal guide star qualities, and in other observing modes.

[5] PACS ICC technical note PICC-MA-TN-003 (M. Nielbock, 2013).