Astrometric calibration

The Pointing System of the Herschel Space Observatory: description and performance

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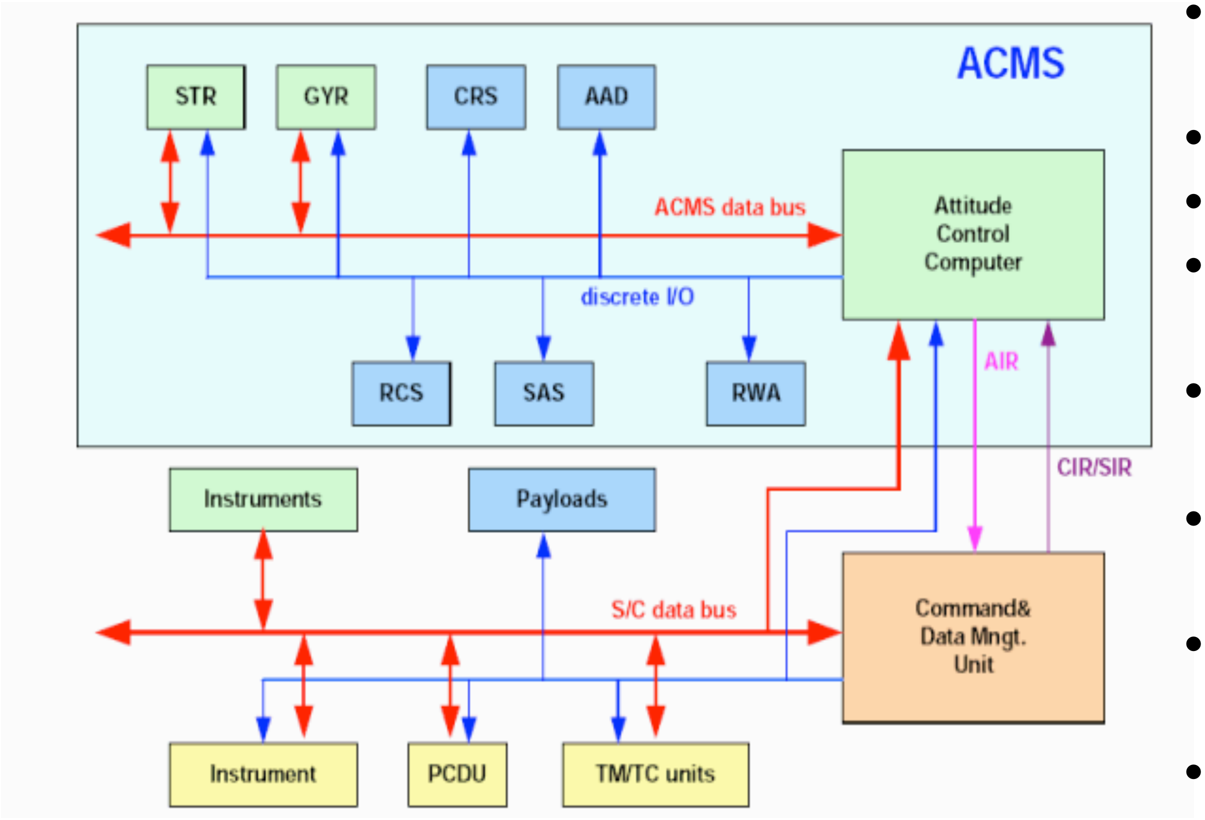
ACMS basics

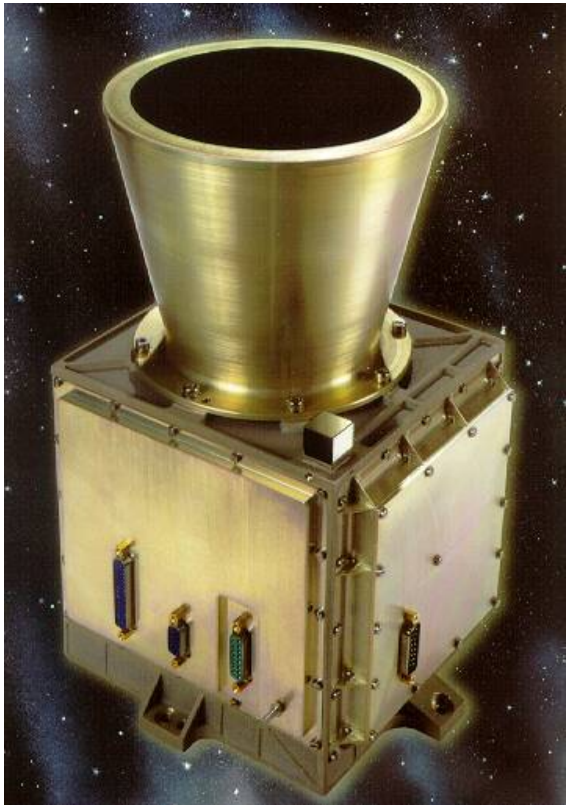
The control of the positioning of the Herschel spacecraft is carried out by the Attitude Control and Measurement System (ACMS). Its main components are:



- Attitude control computer (ACC)
- Gyroscopes (GYR)
- Star trackers (STR)
- Reaction control system (RCS)
- Reaction wheel assembly (RWA)
- Sun acquisition sensors (SAS)
- Coarse rate sensors (CRS)
- Attitude anomaly detectors (AAS).

ACMS basics: STR

- The Herschel S/C has two redundant autonomous star-tracker units (STR)
- Ability to determine the inertial position from "lost in space"
- FoV: 16.4×16.4 deg^2
- Onboard catalog, based on Hipparcos, some 3599 stars contained (2974, i.e. 83% trackable).
- Minimum 3 stars, 9 is the maximum due to HW limitations.
- STR bias is the largest contributor to APE and is pixel-dependent (some 0.8" $\times\sqrt{2}$)
- Enhanced performance mode: "interlaced mode", only applicable if $\geq$ 15 stars in FoV. The STR samples at twice the nominal frequency (4 Hz), 9 stars at a time.



ACMS basics: GYR

- The Herschel S/C uses hemispherical resonating gyroscopes (HRG)
  - Consist of a thin-walled quartz shell that is energized by an electrical field to produce an imperceptible vibration pattern within itself.
  - Used to sense and respond to changes in the inertial orientation of it spin axis.
  - Rate/rate-integrating gyros provide high-precision measures of the S/C angular rate.
- The Herschel's ACMS is provided with four gyroscopes mounted in a tetrahedral configuration.
- The four gyroscopes are hot-redundant. The fourth gyroscope is not used for control, but serves to detect an inconsistency in the output of the other three.

ACMS: Attitude control and measurement

- Estimates of the satellite attitude quaternion and inertial rate vector are obtained combining measurements data from GYR and STR.

- The estimator is based on a 'model replacement approach' in which a dynamical model for the evolution of the quaternion states is replaced by integration of the kinematics' equations of motion, driven by angular rate measurements from the gyro.

- In the nominal estimator the state vector is propagated from the previous estimate using the gyro data. This is then combined with the latest STR measurement to obtain an updated state estimate which is subsequently used for control.

- The actuation is performed by means of the reaction wheel assembly (RWL).

The Attitude History File

- The attitude history file (AHF) is produced by the Flight Dynamics Team per OD basis.
- It packs the ACMS SCM TM generated at 4Hz for slew, point and line scan operations.
- Formatted in ASCII
- Includes on-board time, commanded attitude, filtered attitude, X, Y, Z calibrated rates, SAA, quality flags etc.
- Transferred automatically to the HSC within 8 hours of the end of the OD. It triggers the auxiliary processing chain.

- The pointing product:
  - Re-packs the information contained in the AHF, combined with up-link information from the POS file.
  - It consists of sequences of table data sets including: on-board time, commanded attitude, ACMS-computed attitude (“filtered” attitude field), ground-recomputed estimate (“gyro-propagated” attitude field), attitude error estimates, number of tracked stars, etc.
  - Produced per OD, but sliced per observation.

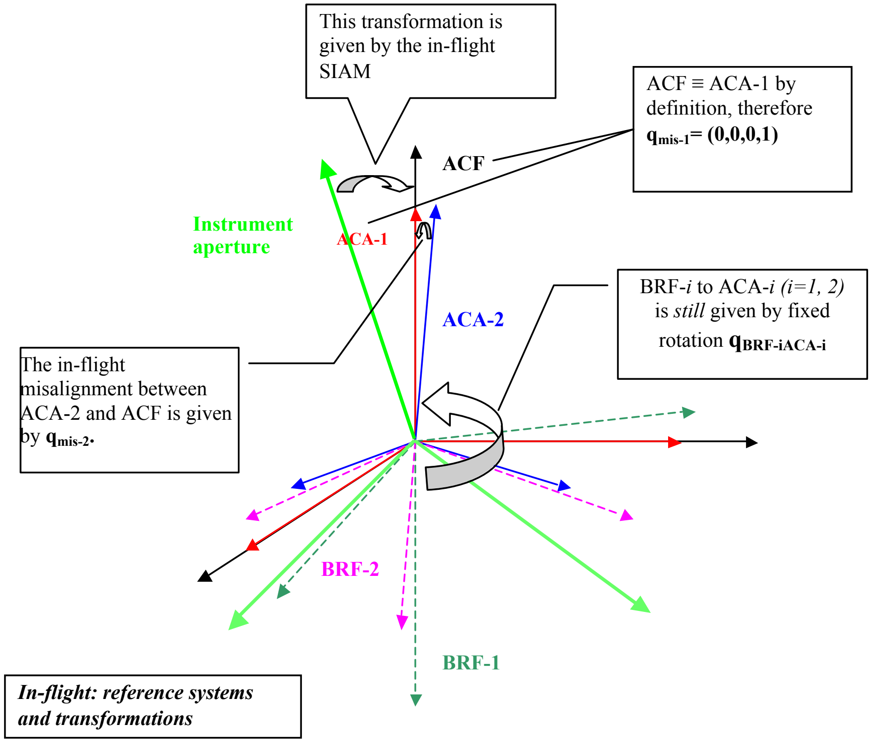
- The ACMS Telemetry product:
  - Contains everything required to re-estimate the S/C attitude from scratch.
  - Sliced per observation, uses essential TM, SCM TM and DTM.
  - Includes many ACMS database parameters as metadata
  - Data records include estimated attitude quaternion, STR quaternion, calibrated gyro rates, IDs, positions, magnitudes and colours of tracked stars, GYR calibration parameters etc.

- The S/C-Instrument Alignment Matrices' (SIAM) product:

$$\mathbf{u}_{INS} = DCM_{INS-SCA} \cdot \mathbf{u}_{SCA}$$

$$\mathbf{u}_{SCA} = DCM_{INS-SCA}^{T} \cdot \mathbf{u}_{INS}$$

- ✓ One rotation matrix (array dataset with Double2d 3 x 3 object) per instrument, i.e. 2 matrices for PACS, 56 matrices for HIFI and 75 matrices for SPIRE.
- ✓ For astrometrical purposes, there are two valid SIAM files across the whole mission: 0122_0001 (OD < 320) and 0341_0001(OD ≥ 320)
- ✓ The full history of Herschel SIAM files can be tracked at:

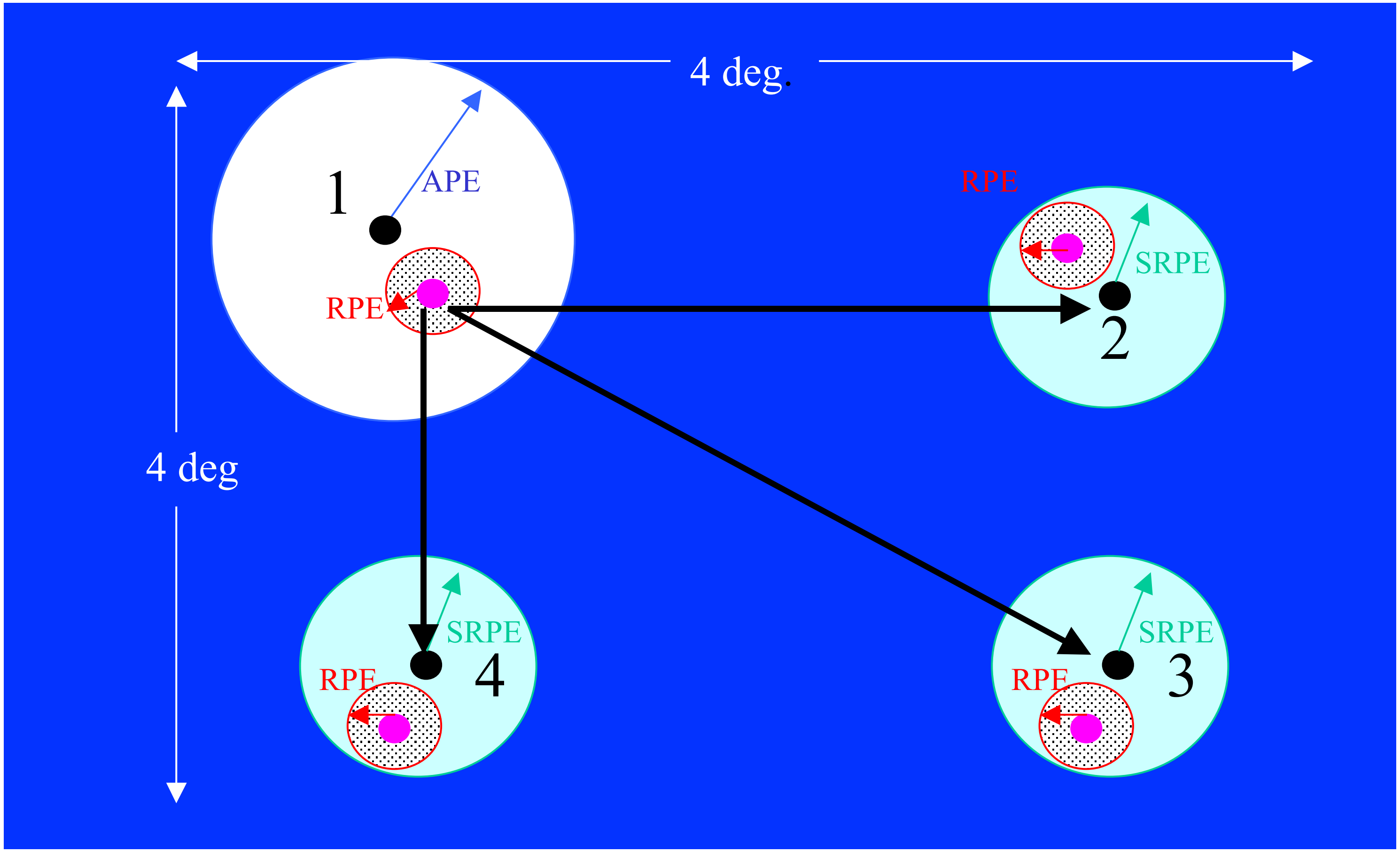


http://herschel.esac.esa.int/twiki/bin/view/HSC/SIAMupdates

Pointing performance definitions

- Absolute Pointing Error (APE)
  - Angular separation between the desired direction and the instantaneous actual direction
- Absolute Measurement Error (AME)
  - Angular separation between the actual and the estimated pointing direction (a posteriori knowledge)
- Pointing Drift Error (PDE)
  - Angular separation between the average pointing direction over some interval and a similar average at a later time
- Relative Pointing error (RPE) or pointing stability
  - Angular separation between the instantaneous pointing direction and the short-time average pointing direction at a given time period (in this case 60 sec)
- Spatial Relative Pointing Error (SRPE)
  - Angular separation between the average orientation of the satellite fixed axis and a pointing reference axis which is defined to an initial reference direction

Pointing performance definitions: SRPE



The first point within a raster is found with the accuracy of APE. The remaining points must be found with an accuracy of SRPE RELATIVE to the initial found point.

Pointing performance definitions

- Main error contributors
  - AME, APE
    - Position-dependent bias within STR ← Also main contributor to SRPE!
    - Residuals from calibration
    - Thermo-elastic stability of the structural path between STR and FPU
    - Instrument LoS calibration accuracy w.r.t. ACA frame
  - PDE
    - Thermo-elastic stability
  - RPE
    - Noise in the control loop: STR+Gyro noise attenuated by Kalman filtering.
    - Quantization of the RWL (digital to analog conversion)

Pointing performance: historical summary

- The main calibration figures were derived in the Performance Verification (PV) phase:
  - ✓ The Spacecraft/Instrument Alignment matrices (SIAM) were derived by planning and executing dedicated calibration observations with the three instruments, as described in the *Herschel Pointing Calibration Plan.*
  - ✓ The main figures of merit (APE, SRPE, RPE) were derived from PACS photometer PV phase observations.
  - ✓ The pointing drift dependency on the Solar Aspect Angle (SAA) was also assessed (and estimated only important for $\beta \leq -20°$)
- The Routine Phase pointing calibration plan goal was twofold: on the one hand, to provide a periodic verification of the pointing calibration (alignment), and on the other, to detect potential variations of the pointing performance.
- We have performed more than 1,000 RP pointing calibration observations
- The PACS Photometer in point-source mode (with dithering) and the blue filter was mostly used.
- But we also included some scan map observations (PACS Photometer mini-map mode). Pointing performance similar to that obtained in point-source mode.
- Also, an accurate STR2-STR1 alignment calibration was performed in OD732 (44 calibration observations, that also served to estimate the pointing accuracy with the backup STR unit).

Pointing performance: historical summary

- One of the main pointing issues found along the mission is the existence of the so-called "speed bumps" observed in scan maps, caused by "warm" pixels in the STR CCD. This was alleviated/ corrected by lowering the reference temperature of the STR CCD to -10°C This was done in **OD320**.
- A side effect of this action was the occurrence of STR focal length (plate scale) errors, introduced by the STR CCD temperature variation. These produced systematic, orientation-dependent offsets.
- The problem was partially corrected by applying a 1D STR focal plane correction, that took place in **OD762**
- **The current on-board performance** has greatly improved thanks to three major developments, implemented step by step.
    1. In a first step (tested in **OD858** and used from **OD866** to **OD1010**), a linear 2D STR FP correction was uploaded, boosting the pointing performance to APE ≈ 1.0 – 1.1 arcsec
    2. In a second step (since **OD1011**), the full STR FP distortion correction (8 polynomial coefficients per axis), computed by the PACS ICC was uploaded, producing a further improvement in the performance, APE ≈ 0.8 – 0.9 arcsec.
    3. In a third step (since **OD1032**), several (73) stars from the STR catalogue that were deemed by the PACS ICC as "dubious" due to positional uncertainties and/or high proper motions were removed from the tracking catalogue (the "tracking flag" was set to zero, and thus the stars can be used for acquisition but no longer for guiding), arriving to a final figure APE ≈ 0.8 arcsec, quite homogeneous across the sky (assuming that a sufficient number of tracking stars are available).
    4. **BUT SEE CAVEAT BELOW REGARDING PERFORMANCE AT "MILDLY" WARM ATTITUDES!**

Pointing performance: historical summary

- Therefore, so far we can distinguish five mission periods regarding pointing performance:
  1. From launch to OD319
  2. From OD320 to OD761
  3. From OD761 to OD865 (excluding OD858)
  4. OD858, and since OD866 → **MAJOR MILESTONE**
  5. Since OD1011 (and OD1032)
- The detailed pointing history can be tracked at: http://herschel.esac.esa.int/twiki/bin/view/Public/SummaryPointing

1st PERIOD (to OD320)

- The most representative APE estimate was derived using PACS photometer point source observations during the Performance Verification (PV) Phase.
- A large set of observations (some 250) in six ODs (38, 64, 86, 92, 101 & 104) were used to derive the PACS photometer P01_0 aperture position and also the absolute pointing performance figure.
- In addition, a large pointing campaign was implemented in OD274 to determine the pointing performance depending on the STR interlacing (il) mode: il-disabled (up to 9 stars tracked at a time, at 2Hz sampling rate) and il-enabled from 15 to 18 stars sampled alternatively in two "planes", at 1Hz rate). The results are summarized below:
- Therefore, it is safe to assume APE ~ 1.9-2 arcsec for that period.

Table 1: APE measurements (1^{st} period)

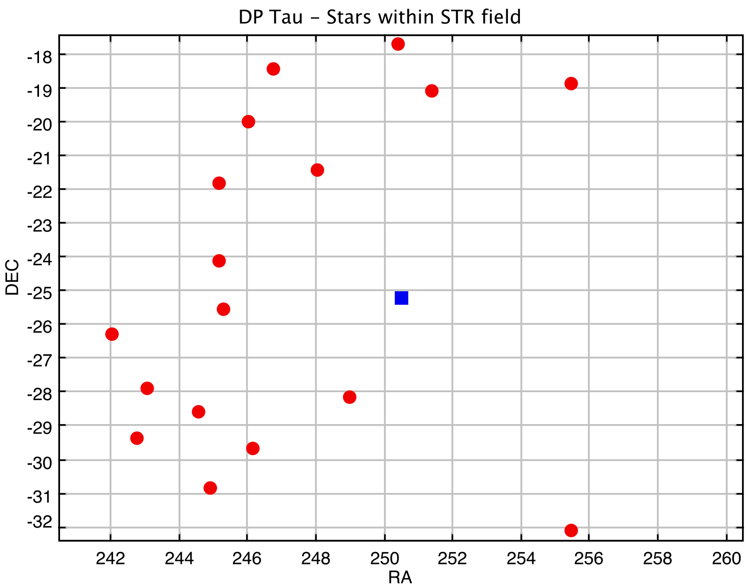
	$\langle \Delta Y \rangle$ (arcsec)	$\langle \Delta Z \rangle$ (arcsec)	σ_Y (arcsec)	σ_Z (arcsec)	APE (arcsec)
OD 38-104 (250 meas.)	–	–	1.09	1.56	1.90
OD 274 (all, 102 meas.)	-0.45	-1.71	1.23	1.51	1.94
OD 274 (il-disab, 55 meas.)	-0.35	-1.67	1.23	1.72	2.24
OD 274 (il-enab, 47 meas.)	-0.57	-1.75	0.93	1.22	1.53

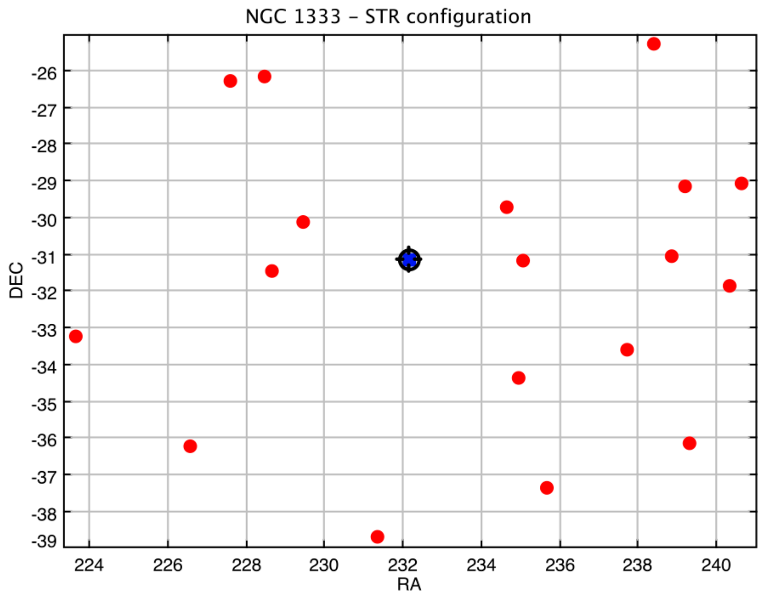
2nd PERIOD (OD320 – 762)

➢ The existence of of a potential pointing problem was revealed by the variations of the dispersion of the distribution of pointing calibration observations (outstanding increase in cycles 23-31 and decrease thereafter, see table in next page) and the growing number of pointing outliers reported by users.

➢ This was reported to FDS. The investigation carried out demonstrated the existence of a "focal length error" (actually a STR CCD plate scale error) as large as 14.2µm (and different in both Y and Z directions) that could result in systematic, boresight-dependent offsets of up to ±8 arcsec.

➢ Moreover, the investigation of pointing outliers revealed that in all cases, the distribution of tracked stars within the STR field was quite asymmetric.



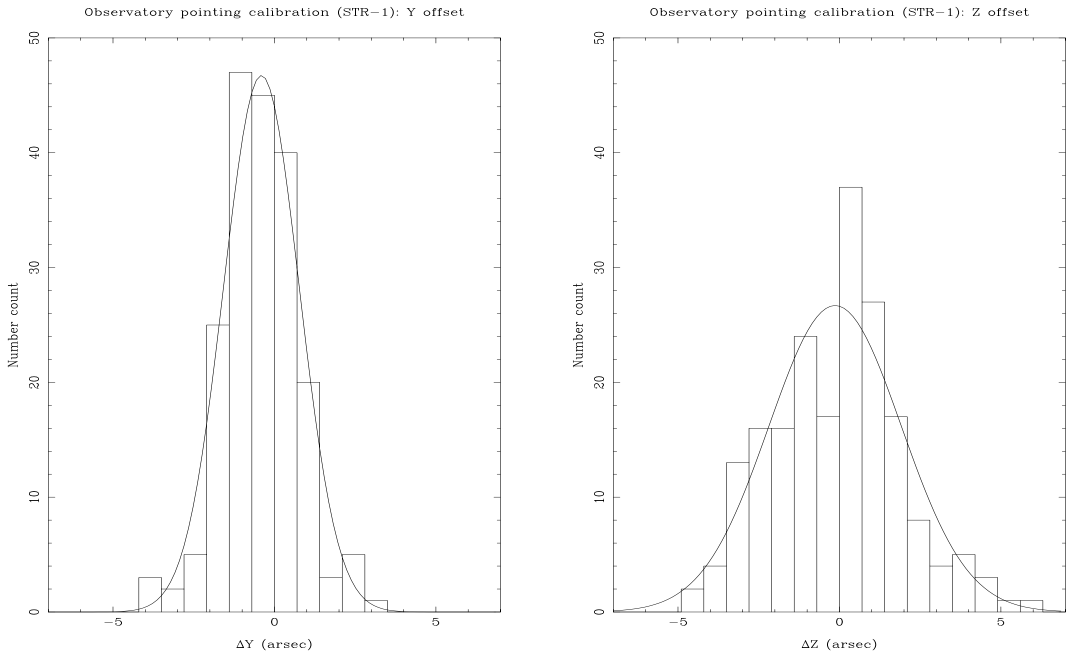


Evolution of the APE

Cycles/OD range	No. obs.	<ΔY> (arcsec)	<ΔZ> (arcsec)	σ_Y (arcsec)	σ_Z (arcsec)	APE (arcsec)
15-22 385-496	45	-0.83	-0.17	0.85	1.80	1.99
23-31 497-622	51	-0.58	-0.30	1.33	2.26	2.62
32-36 623-692	40	-0.08	0.19	1.05	2.03	2.28
33-36 637-692	34	-0.16	0.56	1.06	1.67	1.98
37-39	22	-0.01	-0.58	1.10	1.19	1.62
OD731	17	0.27	-0.57	1.12	2.05	2.33
OD733	21	-0.62	0.55	1.28	2.65	2.95

Pointing calibration figures (averaging up to cycle 40)

Cycles/OD range	No. obs.	<ΔY> (arcsec)	<ΔZ> (arcsec)	σ_Y (arcsec)	σ_Z (arcsec)	APE (arcsec)
15-40 385-733	196	-0.40	-0.13	1.17	2.05	2.36



Largest outlier at 6.88 arcsec from the barycenter of the distribution

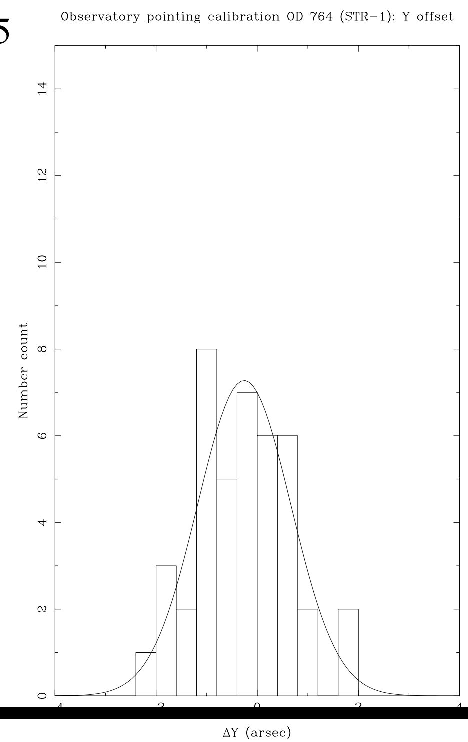
Corrective actions: 1D correction

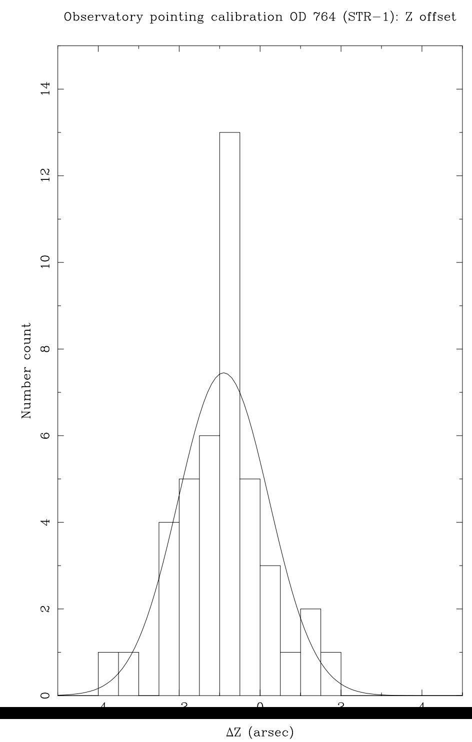
- Unfortunately, the plate scale error affected mainly to STR-1, with a negligible effect on STR-2 (due to the initial detector position). This was evident in the performance figures achieved with STR-2.

- A first on-board corrective action was performed in OD762, by up-loading a common (for both Y and Z axes) correction factor.

- The pointing performance was revisited in OD764 (42 pointing calibration observations), with very positive results:

- max. displacement w.r.t. average position = 4.55 arcsec
- <ΔY> = -0.26 arcsec
- <ΔZ> = 0.90 arcsec
- σ_Y = 0.92 arcsec
- σ_Z = 1.12 arcsec
- APE = 1.45 arcsec





2D correction

➢ The 2D correction (i.e. separate correction factors to the Y and Z axes) was tested in DTCP858. The first assessment done by FDS was very positive.

➢The pointing performance was verified in OD858 by means of of 43 pointing calibration observations, and the results pointed towards sub-arcsec accuracy:

➢max. displacement w.r.t. average position = 2.44 arcsec

➢ <ΔY> = -0.27 arcsec

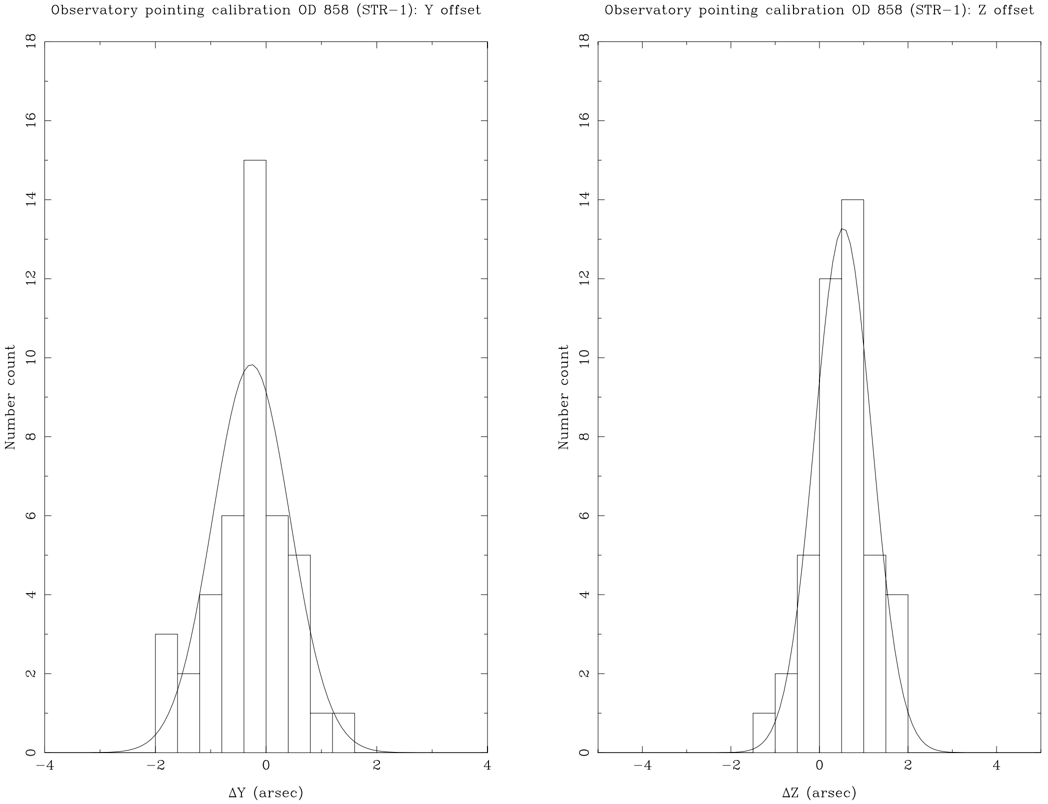
➢ <ΔZ> = 0.54 arcsec

➢ σ_Y = 0.70 arcsec

➢ σ_Z = 0.65 arcsec

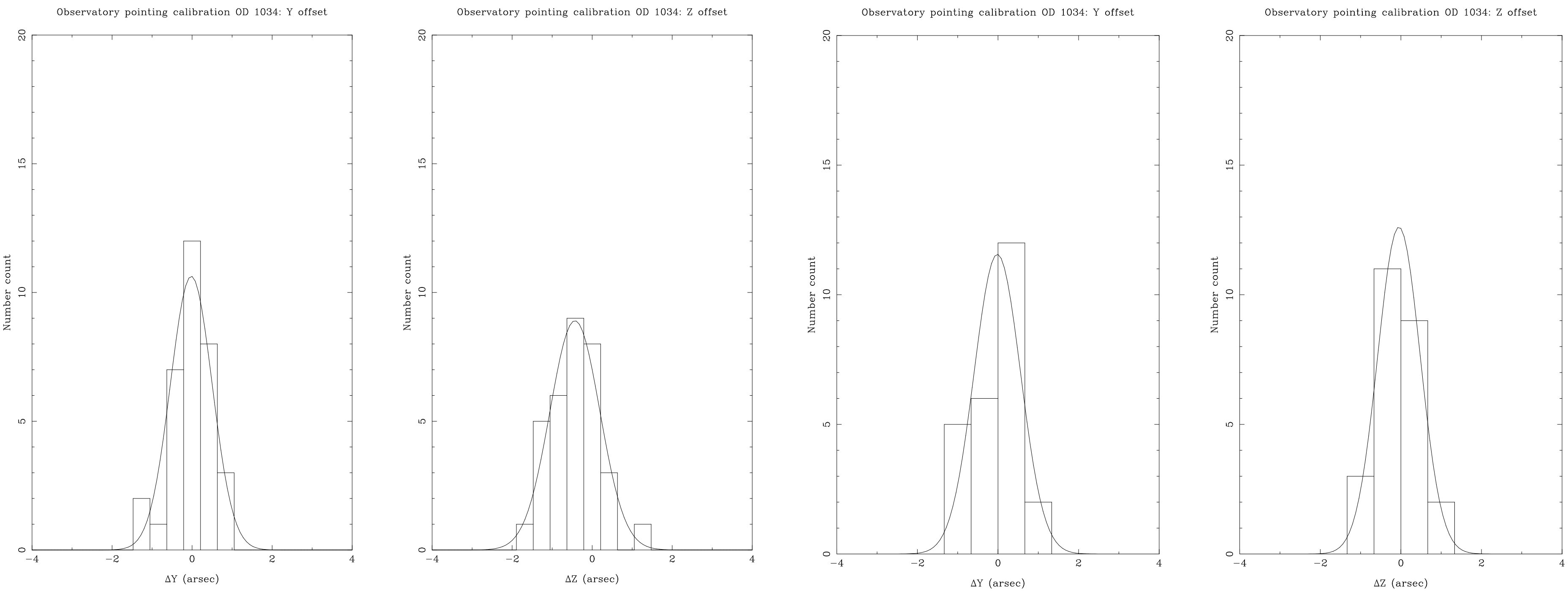
➢APE = 0.95 arcsec

➢The 2D changes were made permanent in OD866.



OD1034: full 2D STR correction and clean catalogue

➢ For this exercise, the sample was divided into 2 “subsamples”, “BAD” (containing stars removed from the tracking catalogue) and “GOOD” (no suspicious stars within the FoV). As expected, the results are very similar.



“BAD” sample (33 stars):

➢ APE = 0.81 arcsec

“GOOD” sample (25 stars):

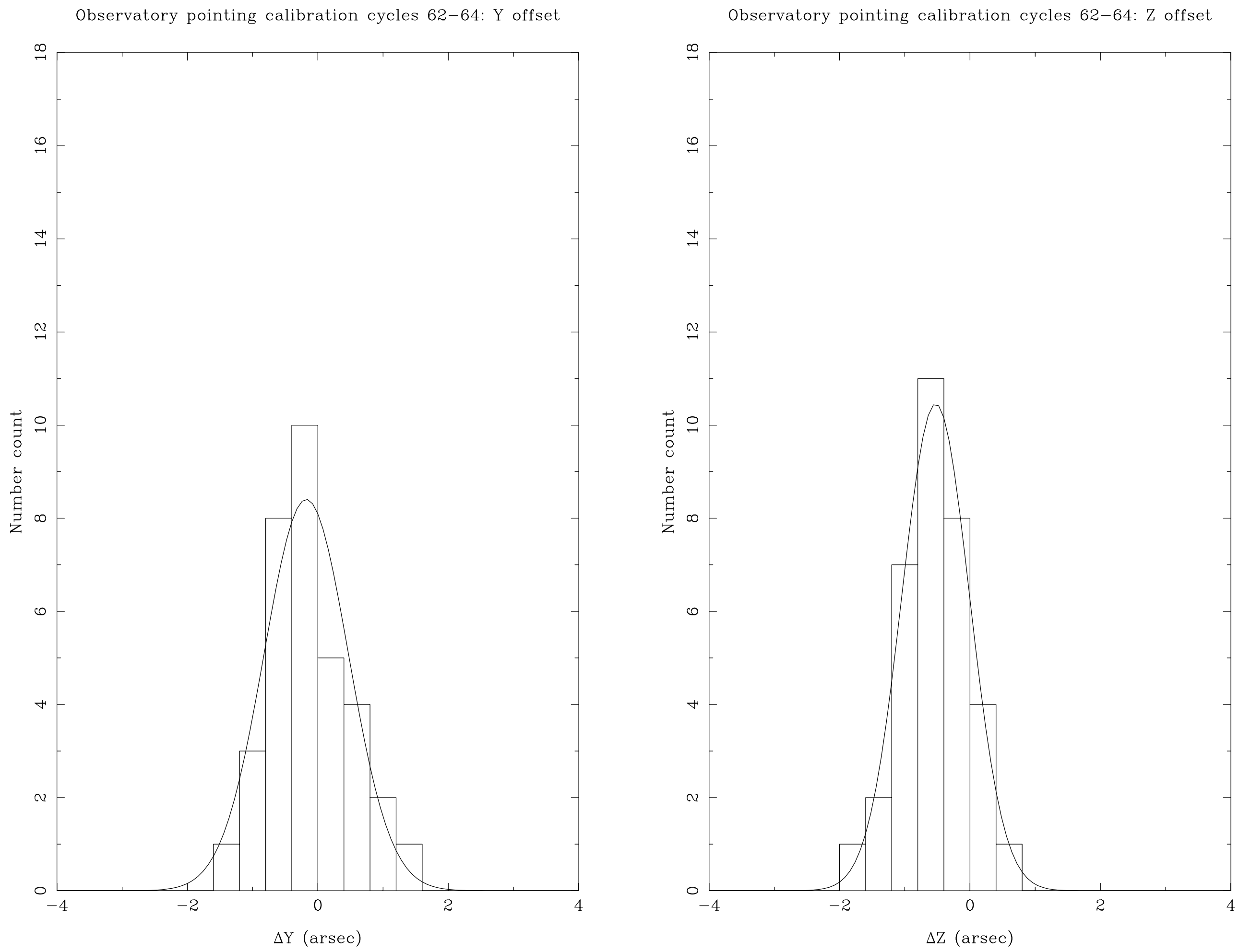
➢ APE = 0.78 arcsec

Pointing performance: current status

➢ After resuming the routine calibration measurements everything indicated that the Herschel's pointing system was performing well:

a)APE ~0.83 arcsec (chop-nod mode, up to cycle 64)

b)APE ~0.87 arcsec (scan map mode, up to cycle 67)



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… but, after accumulating routine observations…

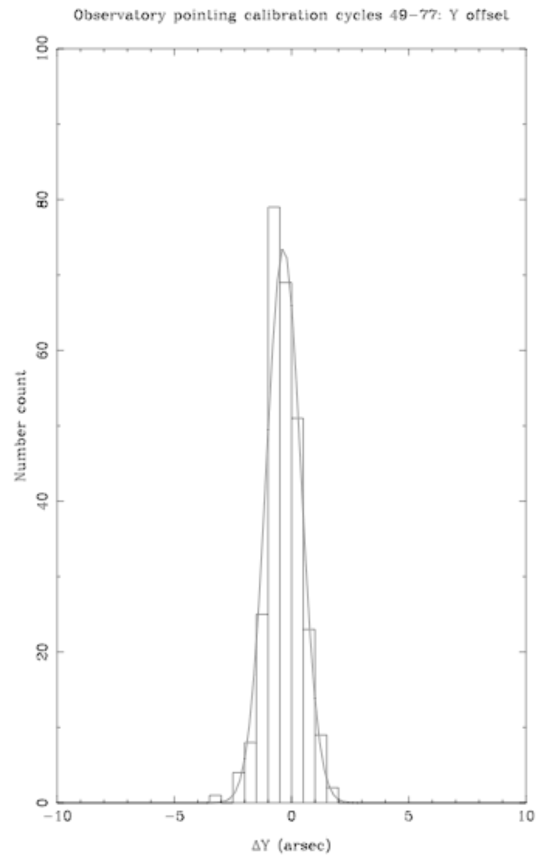
➢ Since OD 866 (main STR FP update), we have accumulated an outstanding set of pointing calibration observations.

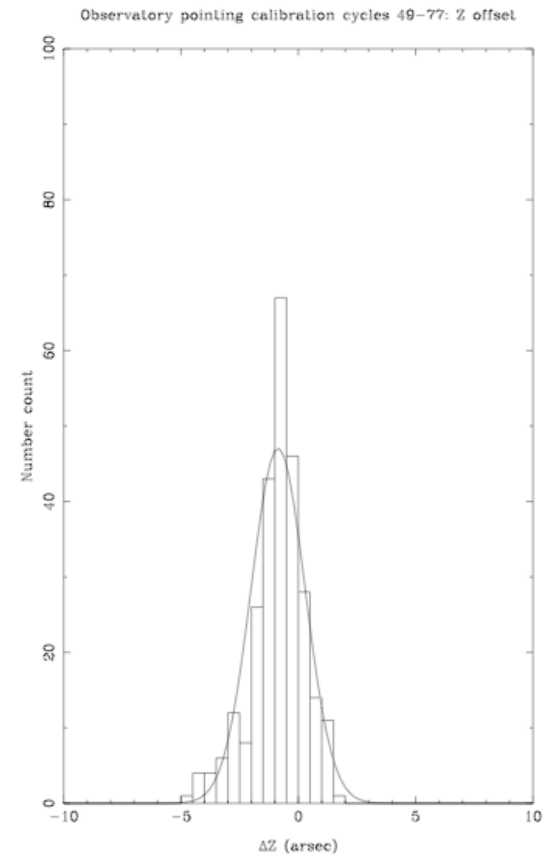
➢ We have analysed 271 pointing calibration observations in the period comprising cycles 49 to 77 (OD 872 to 1266).

➢ Rather large outliers are observed, and a secondary peak towards –Z is clearly observed. Moreover, a relatively large offset is seen in the average Y, Z position.

- max. displacement w.r.t. average position = 3.68 arcsec
- $<\Delta Y>$ = -0.34 arcsec
- $<\Delta Z>$ = -0.86 arcsec
- σ_Y = 0.73 arcsec
- σ_Z = 1.15 arcsec
- APE = 1.36 arcsec

➢ This indicated that something else was affecting pointing. As suspected, was related to SAA.





The impact of warm attitudes

➢ We have done a thorough study of the evolution of the pointing offsets across the whole period.

➢ The Y axis shows no trend (just random dispersion around zero offset)

➢ The Z axis shows a clear trend towards negative Z offsets, with two peaks separated by exactly one year.

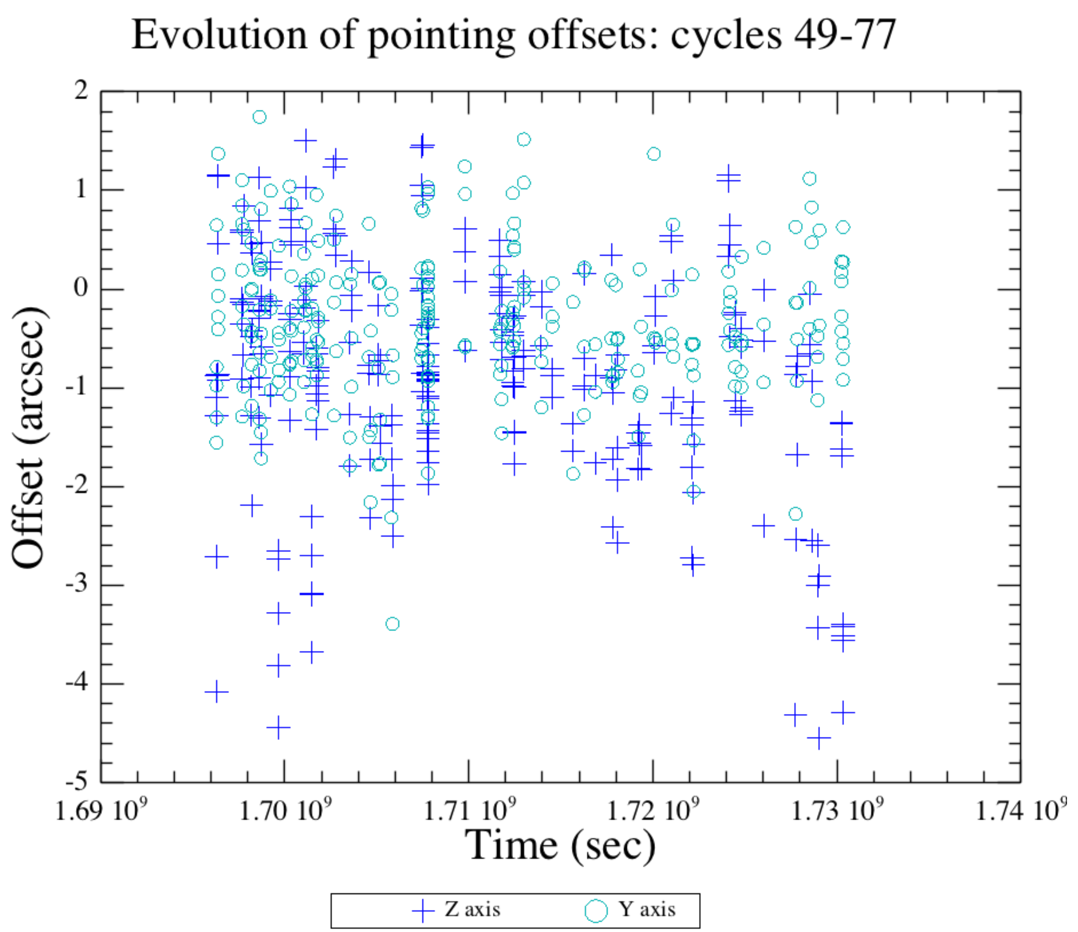
➢ The offsets are apparently not associated to problems (e.g. incorrect astrometry) of the pointing targets themselves.

➢ Rather, the problem seems to be related to the scheduling of long observations at negative beta angles.

➢ In fact, in all but two cases of large Z offsets (larger than 2.5 arcsec), long periods (≥10 hr) at warm attitudes $\beta \leq -10°$, up to -20°) took place 2 or less hours before the time of the pointing calibration observations.

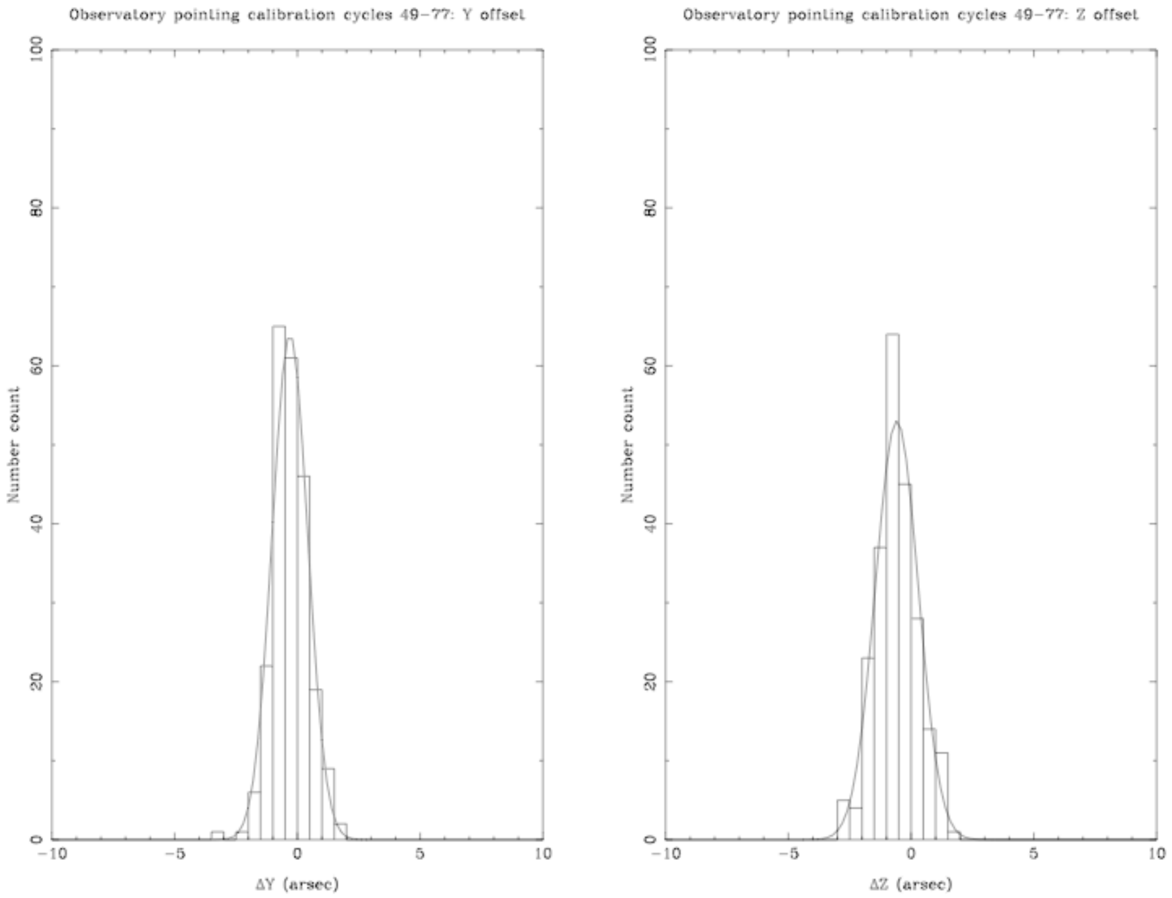
➢ On the other hand, none of the "good" observations investigated (randomly picked) were carried out after negative attitude periods.

➢ **This suggests that the impact of relatively "mild" negative beta angles is larger than previously suspected!**



Pointing performance: current status

- After removing suspicious ODs (872, 911, 932, 969, 1172, 1216, 1236, 1251, 1265 & 1266), the results improve:
    - APE = 1.1 arcsec
- This is better aligned with previous results (~ 1 arcsec APE or better).
- We continue monitoring the Herschel pointing performance, though the number of pointing calibration measurements is being reduced. A final compilation is on-going.
- We are investigating how to parameterize the pointing offset dependence on the SAA. This is a complex issue, since the pointing offset depends not only on the SAA of an observation, but also on the previous values of SAA. Time scales of the pointing drift are not properly known.



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Other pointing figures

- **Interlacing**: we have observed a statistical reduction of the APE figure by ≈ $1/\sqrt{2}$ when 18 stars are tracked
- **SRPE**: only measured for small maps (1 arcmin 2×1 rasters):
  - ✓ PV phase result: baseline/goal measurements = 1.52/1.1 arcsec
  - ✓ A more recent estimate (OD858) gave a result of 1.02 arcsec (mixed interlaced & non-interlaced observations).
- **RPE**: The measured value has been found to be within the requirement of 0.3 arcsec: RPE=0.189 arcsec for α Boo and RPE = 0.287 arcsec for the asteroid 19 Fortuna.
- **STR settling time**: checks performed in OD732 indicate that the STR is thermally settled in less than 4h, confirming industry indications.

Roadmap to the improved pointing products

- Correction for systematic, STR focal plane induced offsets: optimally, this should include all the enhancements produced (full 2D correction, sub-pixel structure…
- Attitude estimation improvement, based on:
  a) Gyro propagation
  b) Attitude improvement by batch estimators (least-squares-like procedures)

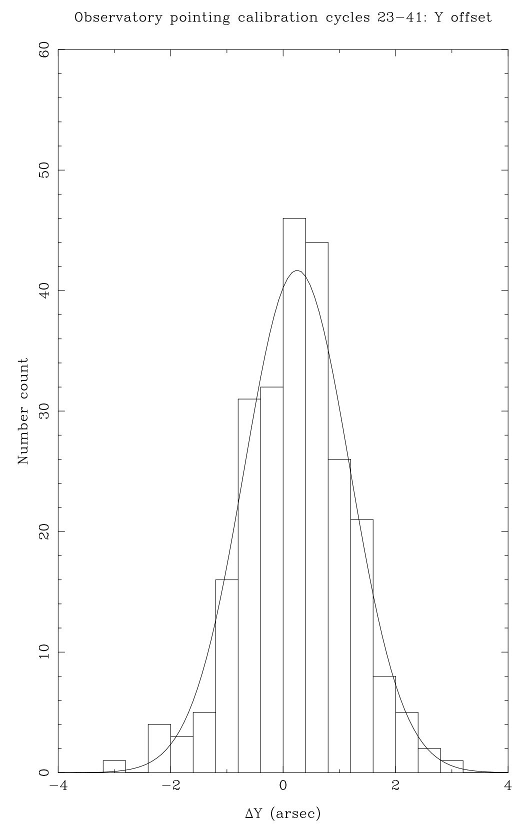
Current improvements

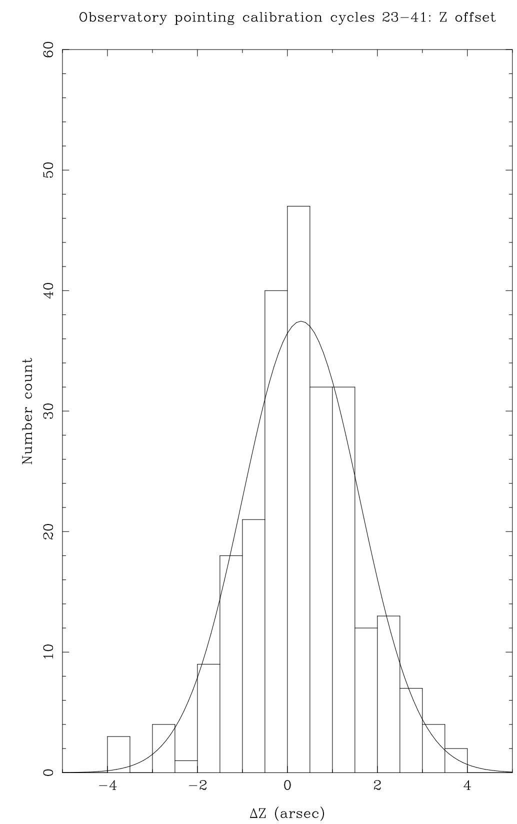
- We have designed a simple offset correction method that applies the STR focal plane 2D linear correction to each attitude within the pointing product.
- Mimics the logic of the STR to get the trackable stars, corrects their positions and determines a new attitude applying the "q Method" from Davenport (1968).
- This correction does not add noise to the attitude samples since is a purely geometric one.
- When the correction factors are set to 1.0, one recovers exactly the input attitude (within $\sim 10^{-10}$ arcsec).
- No additional ACMS information is required (e.g. ID's of tracked stars)
- The correction is already incorporated in the observations reprocessed in the HSA with HCSS V9.1.0, providing corrections for observations in the range OD320 – OD760 and OD761– OD865
- Recently, a correction for early mission phases (OD001-OD319) has been furnished by FDS (not included yet).

Results from reconstruction of pointing calibration observations

- The full set of pointing calibration observations performed in cycles 23 to 41 (245 observations).
- The comparison sample (original pointing information) comprises 113 stars (cycles 23-39)

- max. displacement w.r.t. average position = 4.8 arcsec (was 6.8 arcsec)
- $\langle \Delta Y \rangle$ = 0.25 arcsec (was 0.29 arcsec)
- $\langle \Delta Z \rangle$ = 0.30 arcsec (was 0.18 arcsec)
- σ_Y = 0.94 arcsec (was 1.21 arcsec)
- σ_Z = 1.30 arcsec (was 2.02 arcsec)
- APE = 1.60 arcsec (was 2.35 arcsec)
- Therefore, an outstanding improvement has been achieved, though there is still considerable room for improvement (up to APE ≈ 1 arcsec)
- Tests performed with early mission phase observations (OD 86, 101, 104) indicate that the new FDS correction boosts the APE to ≈ 1.4 arcsec





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On-going/future developments

- Other corrections (specific ODs/obsid's):
  - Corrections for STR switch-over' s
  - Corrections for STR SVV resets (affecting the aberration correction)
  - Ad-hoc offset corrections for observations affected by extreme beta angles
  - Corrections for speed bumps (gyro propagation algorithms already in place)
- Iterative algorithm for computing the initial attitude estimate, use of STR guide stars' information from TM when available (already prototyped)
- But in the near future, the PACS ICC – derived corrections look very promising and are being incorporated into the HCSS software (ia_toolbox_pointing) → **See Helmut's presentation**
- The future? Full attitude re-estimate using batch estimators