Herschel Pointing Accuracy Improvement

Hitting the bullseye from 3234,03 meters distance - History of the Herschel Attitude Control System Pointing Accuracy Improvement

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For the Herschel Space Observatory, launched on May 14, 2009, as part of the ESA Horizon 2000 Science Program, one critical aspect is the pointing accuracy as provided by the Attitude Control and Monitoring System (ACMS). After verification of the in-orbit performance of the ACMS during the Service Module Commissioning Phase, which revealed and corrected for interference from the thermal control of the Gyro Unit (Scalable Inertial Reference Unit), the pointing accuracy was monitored and improved during various campaigns. This paper provides a summary of the measures taken to enhance the performance of Herschel's Attitude Control System beyond manufacturer specifications by eliminating interacting factors such as the identification and removal of "warm" pixels on the Star Tracker CCD, adaption of the focal length in the Star Tracker on-board software stepwise in one, two and then three dimensions and a clean-up of the entries in the Star Tracker on-board Star Catalogue. Herschel is now observing with accuracy in the order below 1 arcsec for the Absolute Pointing Error.

I. Introduction

The Herschel[1] and Planck[2,3] spacecraft were launched together by an Ariane 5 ECA on flight Vol 188 on the 14th May 2009 at 1312:00 z; after having reached their operational orbits around the Sun-Earth Liberation point L2, they do their work as ESA's current infrared observatory and ESA's microwave back-ground radiation survey mission, respectively. They are part of ESA's "HORIZON 2000" science plan. The two spacecraft are operated by the European Spacecraft Operations Centre located in Darmstadt, Germany.

Herschel is a three axis stabilized space telescope. The spacecraft is a multi-user observatory, performing spectroscopy and photometry in the far-infrared and sub-millimeter range of the electromagnetic spectrum. It carries three scientific instruments as payload, the "Photoconductor Array Camera and Spectrometer"(PACS)[4], the "Heterodyne Instrument For Far-Infrared" (HIFI)[5] and the "Spectral and Photometric Imaging Receiver"(SPIRE)[6].

During the scientific pointing modes, the attitude of the spacecraft is determined by the Star Tracker and the Gyro Unit (Scalable Inertial Reference Unit). This paper will describe the history of how the pointing accuracy was improved through in-flight experience in various steps:

1) identification and elimination of interference from the external thermal control of the Gyro Unit
2) identification and removal of "warm" pixels on the Star Tracker CCD
3) APE improvements

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a. adaptation of the focal length in the Star Tracker on-board software
b. two dimensional correction of the CCD (Charge Coupled Device) plane
c. three dimensional correction of the disturbances of the CCD surface

4) clean-up of the entries in the Star Tracker on-board Star Catalogue.

This paper provides the overview of the sequence of measures taken to optimize Herschel's pointing accuracy in flight. It does not claim ownership of the excellent technical work involved which was done by the colleagues as listed in the chapter "Acknowledgments" below.

II. The Herschel ACMS Design

The Herschel Attitude Control and Monitoring System consists of the following set of sensors and actuators[7]:

SAS	Sun Acquisition Sensor
AAD	Attitude Anomaly Detector
CRS	Coarse Rate Sensor Assembly
STR	Star Tracker
RWS	Reaction Wheel System
GYR	gyroscopes; SIRU (Scalable Inertial Reference Unit) hemispherical resonating GYR
RCS	Reaction Control System
ACC	Attitude Control Computer

The architecture of the ACMS is shown in Fig. 1.

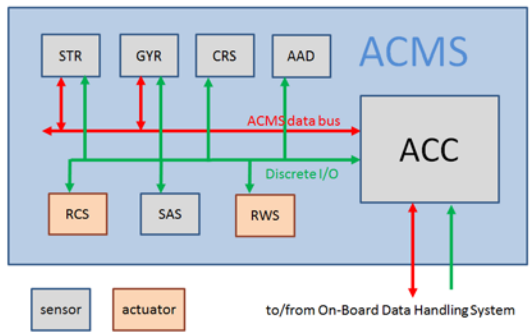

Figure 1. Herschel Attitude Control System

For the subsequent topic of pointing performance improvement in Science Mode, it is worth to explain the Star Tracker and the GYR in more detail.

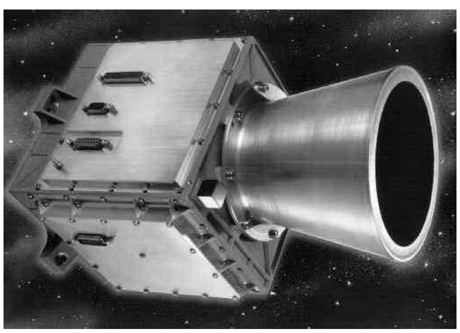

Figure 2. Herschel Star Tracker Unit

The STR used on-board the Herschel spacecraft is built by Galileo Avionica, now called Selex Galileo, and is basically a video camera with a 16.4°x16.4° field of view and an image processing unit that interprets star field images in order to determine spacecraft attitude information, measured with respect to the J2000 inertial reference system. Two identical units are mounted together on the base of the cryostat and are operated in cold redundancy in order to minimise any thermal distortions that may disturb the relative alignment between their bore sight and that of the telescope, which is aligned along the same spacecraft axis but looks in the diametrically opposite direction (i.e. –X for the STR and +X for the telescope). At the heart of the STR is a thermoelectrically cooled CCD (512 x 512 pixels) and an ASIC that provides all of its low-level real-time digital functions, along with some pre-processing operations. All high level functions are managed by software permanently stored in PROM and EEPROM memories and run within an ERC32 microprocessor, which outputs data at 4 Hz onto the ACC's 1553 data bus.

The GYR is built by Northrop Grumman and consists of four Hemispherical Resonator Gyro (HRG) units, each sensitive to rates about one axis, integrated into a single gyro package that is mounted directly onto a service module shear wall panel. The four HRGs are arranged in redundant octahedral tetrad configuration such that any three of four axes provides observability to three orthogonal axes.

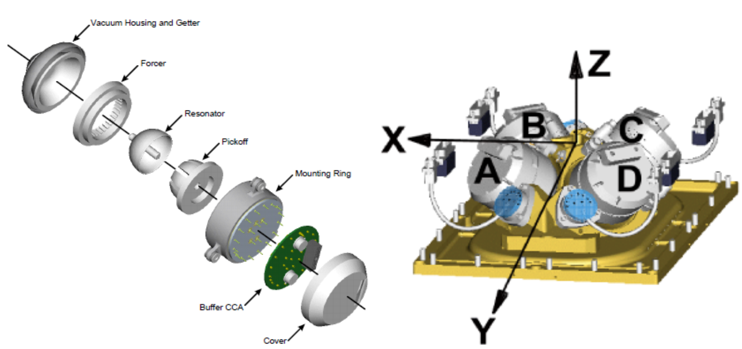

Figure 3. Hemispherical Resonator Gyro Unit & 4-unit assembly

Each HRG has its own set of buffer electronics that transfers its signals to a signal processor via one of two redundant gyro interface electronics units (GYR-E). Each gyro rate signal is then computed by the signal processors and is output at 4 Hz as an accumulated angle and a time tag by the GYR-E, onto the ACC's 1553 data bus. The signal processor also provides precise thermal control for each HRG, via dedicated heater control channels, while the spacecraft's service module provides active thermal control for the GYR's immediate environment, via thermistors located on the unit's mounting plate.

The requirements for the accuracy of the Herschel Pointing Modes are shown in Table 1.

Item	Requirement for LOS [arcsec]	Goal for LOS [arcsec]
APE Pointing	≤ 3.7	≤ 1.5
RPE Pointing (1 min)	< 0.3	≤ 0.3
PDE Pointing (24 hours)	≤ 1.2	-
AME Pointing	≤ 3.1	≤ 1.2

Table 1. Herschel Pointing Modes requirements for pointing accuracy[9]

The definition of the pointing errors are listed below as per Ref.8 and 9:

APE *Absolute Pointing Error*
The APE is the angular separation between the desired direction and the instantaneous actual direction at any time.

RPE *Relative Pointing Error*
The RPE is the angular separation between the instantaneous pointing direction and the short time average pointing direction during some time interval (in the order of 1 minute). This is also known as the pointing stability, or pointing noise.

PDE *Pointing Drift Error*
The PDE is the angular separation between the short time average pointing direction during some time interval and a similar average pointing direction at a later time (the "later time" may be up to 24 hours later).

AME *Attitude Measurement Error*
The AME is the instantaneous angular separation between the actual and the estimated pointing direction. This performance requirement is referred to as "a posteriori knowledge".

III. ACMS in Commissioning

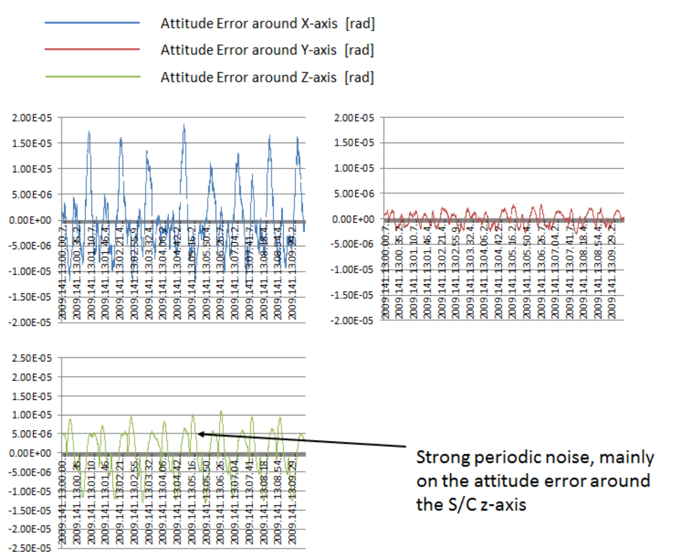

Figure 4. unexpected noisy attitude error calculation in the on-board attitude control law, violating the Relative Pointing Error specifications

During the service module commissioning, on the 19th May 2009, an unexpected behavior of the attitude error around the S/C z-axis was observed as part of the assessment of the performance of the attitude control law in the Science Pointing Mode. As shown in Fig.4., the attitude error around the z-axis determined by the on-board attitude control law showed a noisy signal with a magnitude of 1.0E-5 rad (~2 arcsec). Due to the orientation of the STR as mounted aligned parallel to the S/C x-axis , this was not the expected level of signal for the attitude error around the S/C z-axis. Note that the scale of the plots of the attitude error for all three axes are the same. The attitude error around the x-axis as shown in Fig.4 is greater than the error around the S/C z-axis, but this is expected and according to the design since only one STR with an orientation along the S/C x-axis is providing input to the on-board attitude control law.

The RPE requirements would assume an attitude error in the order of 0.3 arcsec. Furthermore the noise of the signal seemed to be of periodic nature with a period in the order of 72 seconds. See Fig.4.

In the course of the investigation a dedicated test was conducted, excluding the STR from the control loop during Science Pointing Mode. Still the same behavior was observed. Therefore the investigation concentrated on the GYR. Inspecting the attitude error around the S/C z-axis overlaid with the duty-cycle of the external heaters attached to the GYR box, indeed revealed a strong relation as shown in Fig. 5.

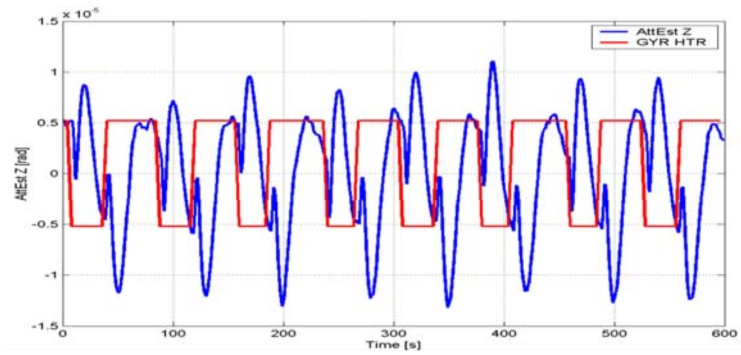

Figure 5. attitude error around the S/C z-axis overlaid with the duty-cycle of the external heaters attached to the GYR box; courtesy of M.Oort, M.Palomba, Y.Roche

Regarding the on-board Failure Detection Isolation and Recovery implementation it shall be noted that with the GYR sum check, the GYR Continuity Check and the GYR-STR Consistency Check in principle there are adequate means to identify signals on the GYR sensors not originating from real motion of the S/C; but the effect of the observed disturbance on the GYR signal was so subtle that none of the above checks triggered.

The anomaly investigation continued with a course of actions also involving tests on ground involving the Avionics Model of the Herschel spacecraft. It was possible to reproduce the observed behavior.

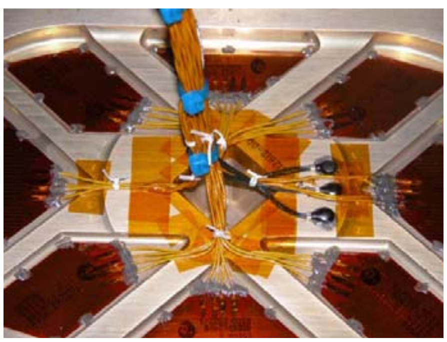

Figure 6. mounting of the heaters on the GYR base plate

The thermal control of the GYR box consists of a thermal control loop inside the GYR box and external heaters glued to the GYR box base plate as shown in Fig.6[10]. The external heaters consists of a set of 8 standard flight heaters with a total power for 45 Watts at 28 Volts. The spikes observed on the GYR signal were clearly induced by the switching of the GYR heaters; the observed signal was also in-line with the thermal cycle of GYR heater of 72 seconds (27 seconds the heaters were ON + 45 seconds when the heaters were OFF)[10].

Figure 7. Plot of the attitude error as seen by the on-board attitude control system at the time when the switching of the external GYR heaters was suppressed.

The correlation between the heater switching and the GYR signal reaction was immediate, therefore a thermal interaction could be excluded. No final conclusions could be reached on the mechanism how the heater switching was propagating into noise on the GYRO rates since something like electromagnetic coupling with the GYR electronics of the sensor head or any other disturbance leaking back to the GYR power lines are believed to be unlikely to affect all four GYR heads in a consistent way, such that none of the above mentioned autonomous on-board checks triggers.

According to the manufacturer, the GYR sensor head need to be operated at the temperature of 70°C to reach nominal performance. The original thermal control design relied on the external heaters – as mentioned above – together with a thermal control internal to the GYR box. The external heaters were supposed to hold an external temperature of the GYR box between 62.5°C and 63°C and were controlled by the Thermal Control Tables as part of the On-board Data Handling System. Thermal analysis provided by Thales Alenia Space (TAS-I) indicated that without the support of the external heaters, the temperature of the GYR box would stabilize around 30°C at the most unfavorable Solar Aspect Angle (i.e. "cold case"). Tests with the actual spacecraft confirmed that the GYR box temperature without the external heaters stabilized in the order of 38°C for a "cold case" Solar Aspect Angle. Also, and even more important, during the in-flight test the internal heater control was able to keep the GYR sensor head temperature stabilized to the 70°C setpoint, even without the support of the external heaters. This led to the solution of the problem by adjusting the Thermal Control thresholds for the external GYR heaters such that the heaters stayed permanently OFF. Fig. 7 shows the on-board implementation conducted on the 25th May 2009 and the positive results, i.e. the termination of the offending signal on the attitude error around the S/C z-axis.

IV. Star Tracker Improvements

Herschel science observations are made via three distinct attitude modes: *fine pointing*, for staring at fixed targets; *line scans*, for mapping large areas of the sky and; *raster scans*, for imaging large areas of the sky via a sequence of fine pointings, though rarely used. The pointing direction for each observation is commanded as a 'quaternion', expressed in the J2000 inertial reference frame, which is related to the bore-sight of the star tracker via an alignment matrix. Images projected onto telescope and star tracker sensors lie within the spacecraft's Y-Z plane because both look along the same spacecraft axis but in opposite directions (i.e. +X and –X respectively).

The pointing performance required for each attitude mode is defined by the associated pointing errors (see Table 1), which were verified in-flight through a series of observational campaigns. The verification of the APE was accomplished by measuring a large number of stars with accurate astrometry using the PACS Photo Point Source (nodding pointing) mode. This assumes that, in the absence of drifts and for a large number of samples, the distribution of the Y and Z offsets (i.e. their actual positions with respect to expected positions) follows Gaussian-like distributions in both Y and Z axes: their mean values representing residual alignment offsets, which can be compensated by updating an alignment matrix, while the dispersions define the APE.

Analysis of the first observational campaign data confirmed the expected performance but also highlighted some specific issues as well as potential opportunities for improvement. In addition, the occurrence of several star tracker anomalies within the first few months of science operations lead to the discovery of a phenomena that also had the potential to degrade pointing performance. The following sections highlight these issues and explain the ways in which they were resolved to give significant improvements in Herschel's pointing performance.

A. CCD Warm Pixels removal

Within the first few months of science operations (August and September 2009), the operational star tracker suffered three reconfigurations that were all triggered by the same failure detection algorithm; the 'GYR-STR cross check'. This algorithm determines whether changes in the STR measured attitude quaternions are consistent with the GYR measured rotation rates by checking against the predicted error, as calculated by the Extended Kalman Filter. If this check triggers, it is assumed that the fault must be with the STR because the validity of GYR data is checked by other, unit specific, failure detection algorithms. However, in order to trigger a unit reconfiguration, a 'spike'

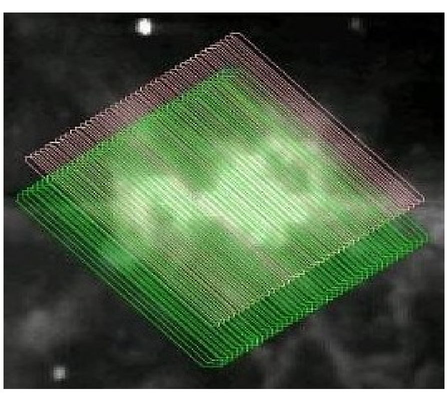

Figure 8. Typical scan map traces by PACS and SPIRE, scanning at ~20"/s

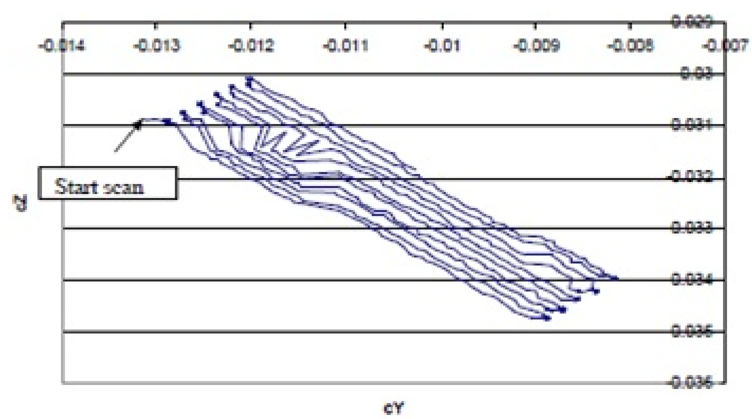

Figure 9. Scan map 'speed bump' due to CCD warm pixel; courtesy of M.Oort.

filter is used to protect against single events and was set to 3 during this period, meaning that three or more contiguous events must have occurred in each case.

Analysis showed that each event occurred during a line scan and that changes in the STR measured quaternions exhibited the same characteristic 'speed bump' behavior, as illustrated in Fig. 9. These sudden errors in attitude measurements (up to ~20 arcsec in the transverse axes and up to ~500 arsec around the bore-sight) occurred in coincidence with the corruption of data (position and magnitude) for one of the stars being track by the STR, while data of other tracked stars were not affected by any additional error.

The best explanation for these the observations was the corrupting influence of a single pixel disturbing the barycenter estimation of the star image as it passed near-by or directly over it. (N.B. as each pixel spans the equivalent of ~115 arcsec, the star image is deliberately de-focused to spread it over a cluster of pixels so that, assuming a symmetrical 'diffusion', its barycenter position can be estimated to arc-second precision).

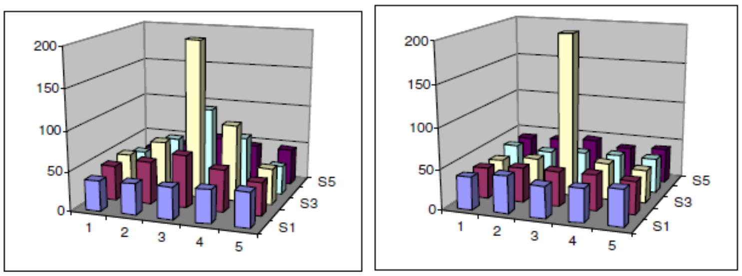

Figure 10. Examples of a real star (left) and a warm pixel (right) having comparable energy; courtesy of A.Bacchetta.

Dumps of the full CCD image were performed to test this theory and, after subtracting the effects of real star images, these showed a sufficient number of 'warm' pixels (i.e. those with noticeably higher energy than the background, as illustrated in Fig. 10, but not high enough to trigger the STR software's defective pixel detection algorithm) to explain the observed behavior. As a consequence, an operational procedure was developed to enable patching of the STR's Defective Pixel Table, which would normally hold the location of automatically detected 'hot' pixels so that the STR could then exclude them from its attitude determination algorithm. This procedure, in conjunction with the associated full CCD dump and on-ground analysis, was first implemented successfully in 14th July 2010 and has been repeated on a routine (monthly) basis ever since.

In parallel with these activities, an investigation was also performed to assess the impact of cooling the CCD in order to reduce both the number and energy levels of the 'warm' pixels with respect to the background values. This approach was taken because the dark current generation law for silicon predicted that the energy value of any 'warm' pixel would halve with every 7°C of temperature reduction. Reducing the CCD's temperature was achieved by simply changing the software value that defines the target temperature of the Peltier cooler's control loop, which was originally set to +20°C but was adjusted down to -10°C on 29th March 2010 after both ground and in-flight tests showed it to be the best compromise value. Moreover, the number of 'warm' pixels detected by the routine CCD dumps now appears to have reached a dynamic equilibrium at a value of around 25, which is much less than the maximum of 128 entries that the Defective Pixel Table can hold.

In addition to these STR operations, the 'spike' filter, which is a settable value within an ACC software table, was increased to ensure that reconfigurations would only be triggered after an extremely large (i.e. 1200) number of 'GYR-STR cross check' instances. Current flight experience shows that, after implementing both the routine updating of the Defective Pixel Table and the CCD temperature reduction, the number of 'GYR-STR cross check' instances is only around three per day and that we have never since experienced more than two contiguous instances.

B. APE Improvements

The STR bore-sight direction vector, expressed as quaternions with respect to the STR frame, is derived from star images detected by the CCD. The image intensity is used to determine each star's magnitude while their relative positions on the CCD define their spatial relationship. Given these basic characteristics, a star catalogue can then be used to uniquely identify the location and orientation of the star field with respect to the celestial sphere and thereby derive the STR's bore-sight direction vector. STR quaternions are generated at 4Hz by the STR's microprocessor software, based upon a series of assumptions about how the STR's focal plane image is distorted by both optical and mechanical effects.

Optical distortions range from simple changes in focal length to more complicated distortions within the focal plane, due to changes in temperature of the STR's optical mounting. Also, mechanical distortions can arise from a physical warping of the CCD plane, due to changes in Peltier cooler temperature. The STR accounts for such distortions during computation of the direction vector via a number of assumed relationships that use both updateable parameters and a set of fixed constants. The following sub-sections discuss the way in which these relationships were assessed by in-flight data and then updated, based upon values derived by on-ground simulations to give the series of APE improvements listed in Table 2.

- **STR Focal Length Correction**

A detailed analysis of attitude determination errors[11] showed a systematic change had occurred after lowering the CCD temperature to reduce the number of 'warm' pixels on 29th March 2010, Herschel's 350th Operational Day (OD350). Further analysis showed that this degradation could be attributed to a change in the STR's assumed focal length (see Fig. 11) and that this could be compensated for on-board by a simple change to the software's assumed focal length, which is held within the unit's EEPROM as a programmable value that can be modified via a dedicated telecommand.

After technical discussions with the Herschel scientists and Industry, the on-board focal length value was updated during a routine CCD dump on 14th June 2011 (OD762) and initial on-ground analysis showed that it had improved the residual focal length error from +14.2 microns to -0.08 microns. More detailed analysis, based upon a set of 96 observations, also showed that this update had also improved the APE from 1.57 arcsec to 1.41 arcsec and that the histogram of star angular separation error was now far more symmetric.

APE Improvement Steps	*APE (arcsec)*
Design Requirement	3.70
In-Flight Verification	1.57
Focal length correction	1.41
2-D distortion coeffs. update	0.95
3-D distortion coeffs. update	0.84
Star Catalogue update	0.81

Table 2. APE Improvement History

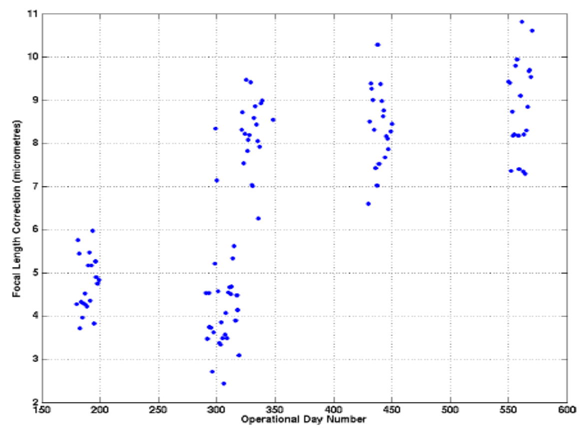

Figure 11. Estimated Focal Length Correction Evolution; courtesy of M.Tuttlebee.

- **2-Dimensional STR Distortion Coefficient Correction**

In addition to focal length, derivation of the STR quaternions also assumes a set of focal plane (Y-Z) distortions that are expressed as 7th order polynomial coefficients, applied with respect to each axis (k0-k7 for Y, h0-h7 for Z) and held in the unit's EEPROM as two fixed data word arrays that can only be modified via direct patching.

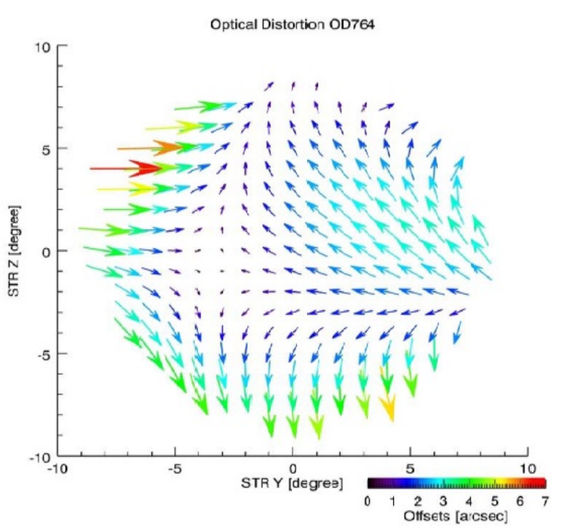

Figure 12. Residual distortions of the STR1 focal plane, after focal length correction in OD760; courtesy of H.Feuchtgruber.

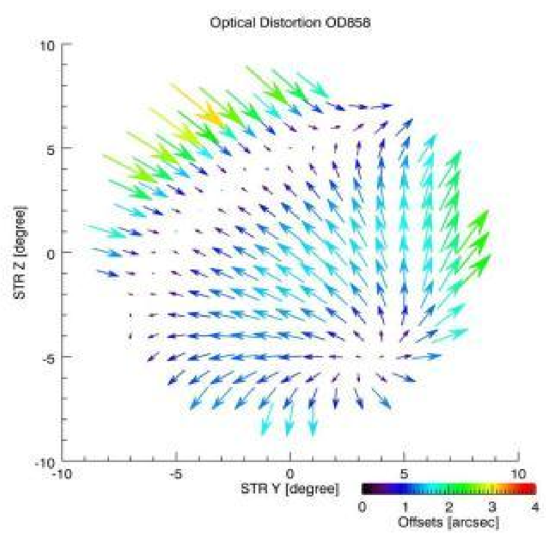

Figure 13. Residual distortions of the STR1 focal plane, after 2-D distortion coefficient update in OD858; courtesy of H.Feuchtgruber.

The analysis that had initially identified the focal length change caused by lowering the CCD temperature had also suggested that attitude determination errors could be further improved by updating these polynomial terms. Moreover, further analysis of the distortion of star positions on the CCD, based upon observations made after the focal length correction (see Fig. 12), confirmed that significant residual errors remained but could be improved significantly by updating some or all of the polynomial coefficients.

After much discussion with the Herschel scientists and Industry, who had derived the baseline coefficients after exhaustive calibration tests on each STR unit prior to delivery for integration with the spacecraft, it was decided to patch the STR EEPROM to update just the 2-D (k1 and h1) coefficients. This was performed in several stages to enable an initial assessment, prior to permanent roll-out of the updated values. The initial update was made on 18th September 2011 (OD858) and data was gathered over 43 observations during OD858, followed by a roll-back to the baseline values on the following day. Analysis of OD858 data showed that the APE had further improved from 1.41 arcsec to 0.95 arcsec and so the updated 2-D distortion coefficients (k1 and h1) were then reapplied on the 26th September (OD866). Later analysis showed that similar improvements had also been made in both the residual distortions (see Fig. 13) and the focal length residuals (see Fig. 14), confirming the benefits of these updates.

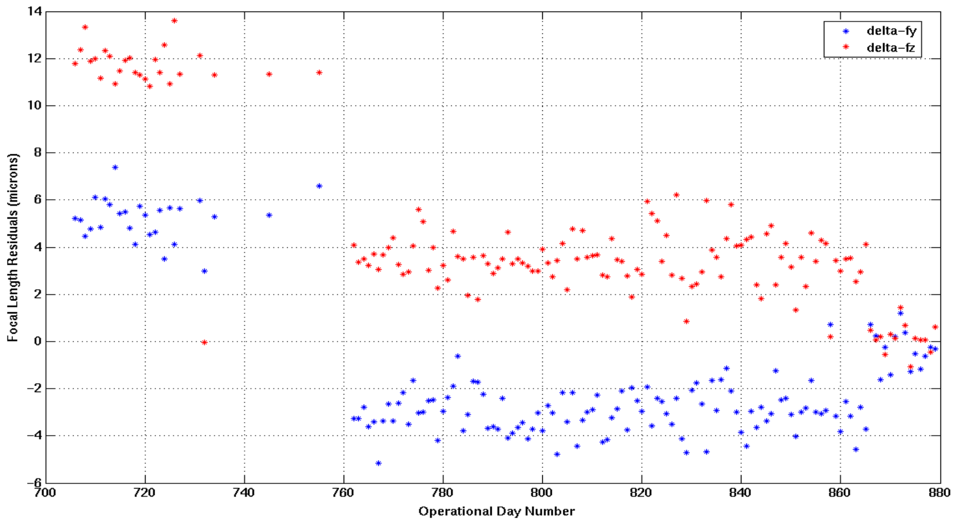

Figure 14. Evolution of focal length residuals after 1-D update in OD760 and 2-D final update in OD866; courtesy of M.Tuttlebee.

- **3-Dimensional STR Distortion Coefficient Correction**

The improvements in overall pointing performance that resulted from updating the 2-D distortion coefficients (k1 and h1) gave confidence to the idea of updating the full set of 3-D distortion coefficients (k0-k7 and h0-h7).

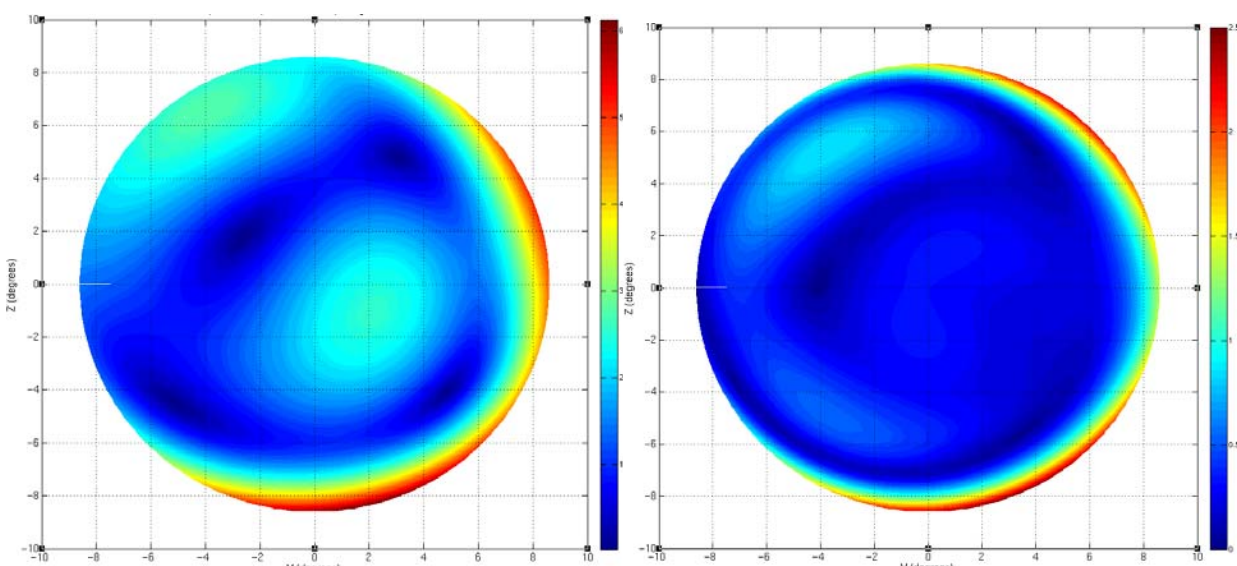

Figure 15. Residual distortion assessment before and after 3-D update in OD1005; courtesy of M.Tuttlebee.

After further discussions with both Industry and the Herschel scientists, new values for the full set of coefficients were derived and then successfully patched within the STR EEPROM on 12th February 2012 (OD1005). Data was then gathered over 24 observations during OD1005, followed by a roll-back to the previous values (i.e. k1 and h1 returned to the values updated during OD866) on the following day. Analysis of OD1005 data showed that the APE had further improved from 0.95 arcsec to 0.84 arcsec and so the full set of updated 3-D distortion coefficients (k0-k7 and h0-h7) was then reapplied on the 18th February 2012 (OD1011).

Later analysis showed that similar improvements had again been made in the residual distortions (see Fig. 15), confirming the benefits of these additional STR software updates.

- **STR On-board Star Catalog Clean-up**

In addition to the optical attributes of the STR contributing to the pointing error budget, i.e. the focal length and the CCD characteristics, also the on-board star catalogue was considered for attitude error improvement. The STR attitude determination algorithms in the Autonomous Attitude Determination mode makes use of two on-board catalogues: the "star catalogue" and the "triad catalogue". During the initial sub-state of the AAD, called Autonomous Acquisition and Coarse Attitude Determination, the STR uses the "triad catalogue" for star pattern recognition. Once the STR has found the coarse attitude in the inertial reference frame, the STR uses then, in the subsequent sub-state called Autonomous Tracking and Fine Attitude Determination, the "star catalogue" for tracking the known stars with reduced tracking windows on the CCD (15x15 pixels).

The "star catalogue" was derived from the Hipparcos star catalogue, selecting for each position in the sky a sufficient numbers of stars to guarantee the best pointing information. Therefore the stars had been categorized in groups of different quality levels. For each region of the sky a trade was made between the minimum number of stars needed to accurately determine the attitude (the more stars the better) and the quality of the star information (position and magnitude). The Herschel on-board "star catalogue" consists of about 3600 stars.

The "triad catalogue" has been built, based on the "star catalogue", by grouping always three of the brightest and closest stars.

For in-flight verification of the STR performance special diagnostic telemetry was defined and is permanently downloaded as part of the Service Module Housekeeping information. These dedicated Diagnostic Telemetry Packets contain the raw star information during the Fine Attitude Determination with a frequency of 1 Hz. Through inspection of this diagnostic telemetry it was found that not all stars tracked during the Fine Attitude Determination provided "good" input to the attitude determination algorithm, but show an offset to the expected barycenter position on the CCD compared to the expected position according to the "star catalogue". One contributing factor for providing an offset in the expected position for some of the "star catalogue" entries is the proper motion. The "star catalogue" provided for on-board implementation prior to launch was compiled with a reference epoch of 31st October 2008. This assumed an original launch date in 2007 and was optimized for the middle of the expected mission duration. After a delay in the launch date occurred, no updated "star catalogue" referring to a new reference epoch was foreseen, since the overall contribution to the expected APE and AME was deemed acceptable. Nevertheless, for a number of stars with a greater proper motion, the difference in position between the reference epoch applied for the on-board "star catalogue" compared to the position calculated for instance for the epoch in 2010 is not negligible. The histogram in Fig. 16. shows the difference in star positions (angular difference) recalculated with a reference epoch 5th August 2011 (green color).

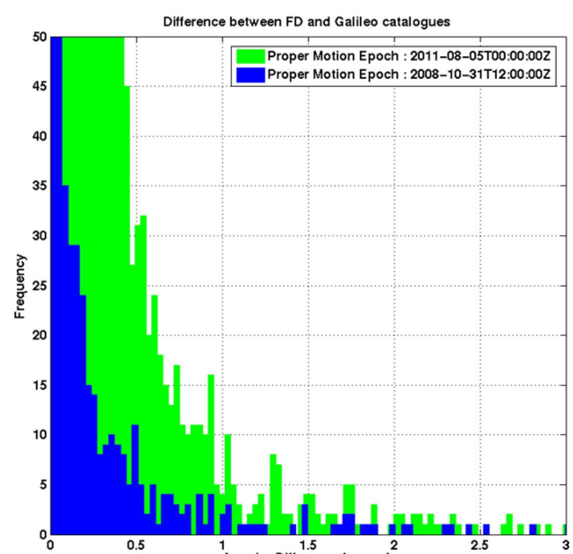

Figure 16. Histogram of star position offset comparing the two reference epochs 31st Oct. 2008 and 5th Aug. 2011; courtesy of M.Tuttlebee.

The determination of the barycenter of star on the CCD as described in chapter IV.A above (i.e. the de-focused image of a star is spread over more than 1 pixel) is also disturbed by other stars or objects nearby or in the background. Those additional signals modify the shape of the defocused star and shift the barycenter.

It shall be noted at this point that indeed the overall pointing performance improvement as achieved through the on-board knowledge of the focal length and the CCD characteristics (as described in the chapters above) was deemed already very satisfactory, while through a clean-up of the “star catalogue” improvement could be reached for a small fraction of individual pointing targets, namely those areas of the sky where the bad stars would be positioned.

In order to remove the most offending entries in the “star catalogue”, independent from what causes the off-position of a star, a pragmatic approach was followed. For the period between 29th March 2010 and 13th June 2011, the operational phase between the lowering of the CCD cooling temperature to -10°C and the 1-dimensional STR focal length update, the position of the barycenter for all tracked stars for all stable Fine Pointing Observations was compared with the expected star position according the on-board “star catalogue”. All stars which provided a ratio below 80% of the measured positions inside a 10 arcsec radius were flagged as “bad stars”. 76 stars were identified to fall into this category. This set was subject to a simulation performed by Dutch Space to verify that none of the “bad star” to be removed would be in a sparsely populated field of the sky such that removing it would reduce the pointing accuracy due to lack of tracking stars, more than due to its poor quality. Indeed, three out of the 76 stars were recommended not to be removed from the on-board “star catalogue”.

For each entry in the on-board star catalogue exists a flag which determines whether the on-board control algorithm makes use of the star during the Autonomous Tracking. For each of the identified and confirmed “bad stars” this flag was updated to “don’t track” on the 10th March 2012.

In order to verify the “star catalogue” clean-up, a dedicated calibration pointing campaign was scheduled by the Herschel Science Centre. As part of the verification of the 3-dimensional STR focal length update, on the 6th March

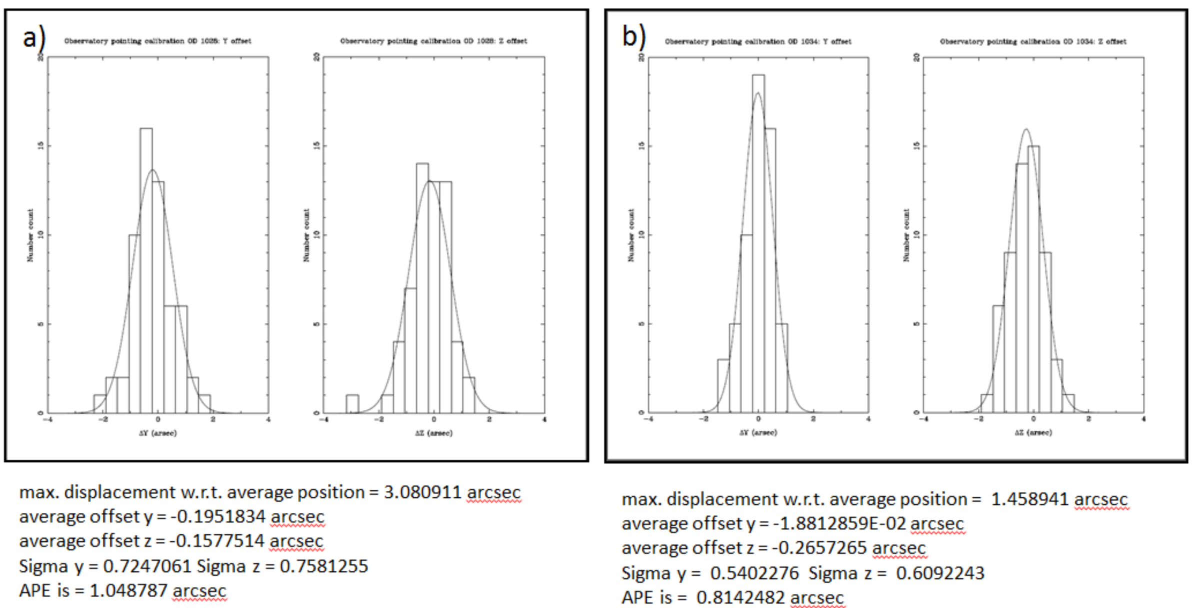

Figure 17. APE improvement after “star catalogue“ clean-up ; a) results obtained prior to clean-up; average APE=1.05 arcsec; b) results obtained after “star catalogue” clean-up; average APE=0.81 arcsec; histograms and figures courtesy of M. Sanchez

2012 a special pointing campaign was run, which partially had selected pointing targets including some of the “bad” stars. The same pointing targets were revisited on the 12th March 2012, after the “star catalogue” clean-up. Fig.17 shows the distribution of the Y- and Z- offset to the commanded absolute pointing direction (as measured by the PACS instrument detector off-set, used as an external reference) for all dedicated calibration pointings prior and after the star catalogue clean-up.

V. Summary

In-flight experience during Herschel operations allowed optimization of the overall pointing performance of the Attitude Control and Monitoring System, to a factor 4.5 better than the requirements. After identification and correction of interference of the external heaters of the GYR box, which indeed had caused a violation of the Attitude Measurement Error, further stepwise improvement of mainly the Absolute Pointing Error was achieved through the removal of warm pixels on the CCD of the Star Tracker, through the correction of the on-board knowledge of the Focal length and the CCD characteristics, and finally through a clean-up of the on-board "star catalogue".

VI. Analogy

In order to illustrate a pointing accuracy in the order of 1 arcsec the following analogy may be helpful. The "bull" inside diameter of a standard dartboard shall be 12,7 mm[12]. With a measured pointing performance of 0.81 arcsec, the Herschel Space Observatory would be able (with a guarantee of 68,2%, i.e. one standard deviation) to hit the "bull" from a distance of 3234,03 meters.

Appendix A
Acronym List

AAD	Attitude Anomaly Detector (on ACC level)
AAD	Autonomous Attitude Determination (on STR level)
ACC	Attitude Control Computer
ACMS	Attitude Control and Monitoring System
AME	Attitude Measurement Error
APE	Absolute Pointing Error
ASIC	Application-Specific Integrated Circuit
CCD	Charge Coupled Device
CRS	Coarse Rate Sensor Assembly
EEPROM	Electrically Erasable Programmable Read-Only Memory
GYR	gyroscopes; SIRU (Scalable Inertial Reference Unit
GYR-E	Gyro Electronics Unit
HIFI	Heterodyne Instrument For Herschel
HRG	Hemispherical Resonator Gyro
LOS	Line of Sight
PACS	Photoconductor Array Camera and Spectrometer
PDE	Pointing Drift Error
PROM	Programmable Read-Only Memory
RCS	Reaction Control System
RPE	Relative Pointing Error
RWS	Reaction Wheel System
SAA	Solar Aspect Angle
SAS	Sun Acquisition Sensor
SPIRE	Spectral and Photometric Imaging Receiver
STR	Star Tracker

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