Herschel Pointing Reconstruction

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this work would not have been possible without contributions from:

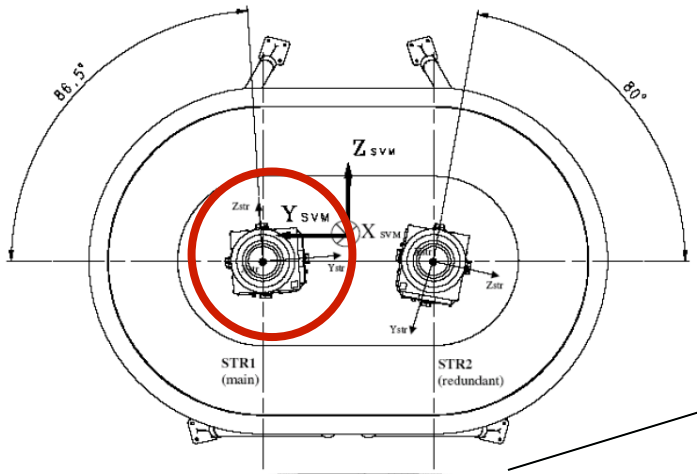
M. Tuttlebee, H. Aussel, A. Poglitsch

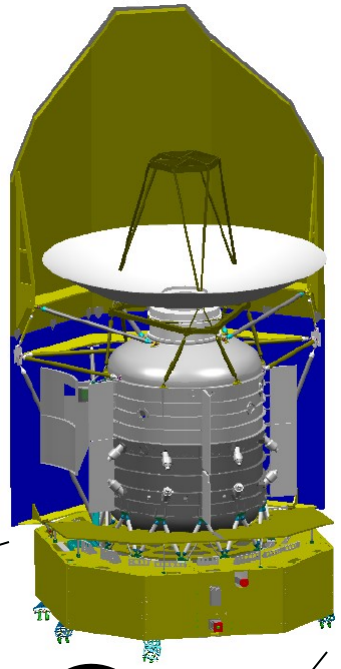
Content

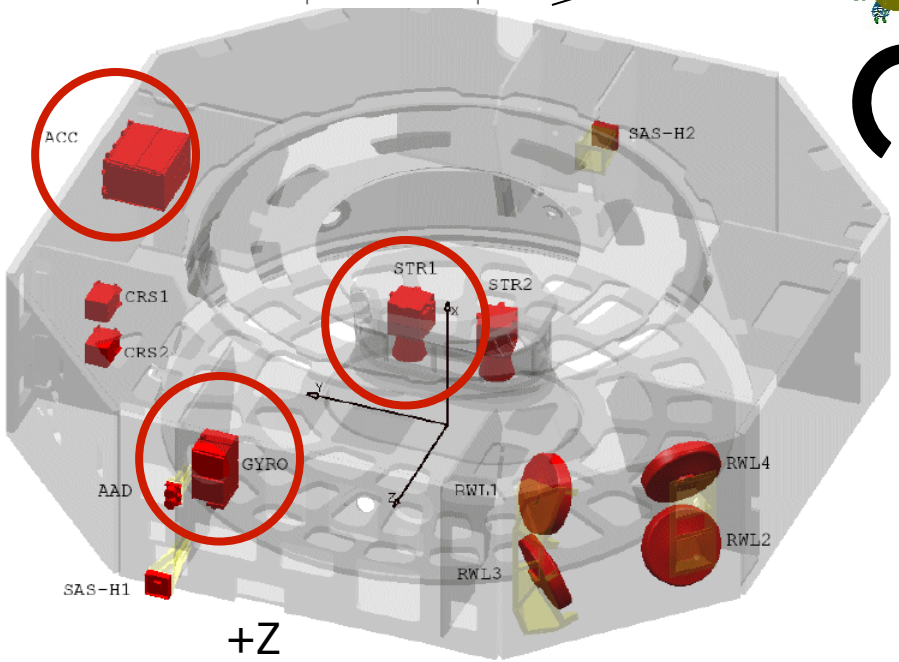
- Introduction
  - The historical aspects of this work are not included here but are supposed to be dealt with in the upcoming "Lessons Learned Meeting"
- Attitude determination from Star-tracker data
  (PICC-ME-TN-041, "Herschel STR-A CCD Sub-Pixel Structure")
- Determination of guide star quality and bad star identification
  (PICC-ME-TN-040, "Herschel Guide Stars, Assessment of Quality";
  "A first look into the STR catalog", 27-July-2011, H. Aussel)
- Reconstruction of the spacecraft pointing jitter
  (PICC-ME-TN-042, "Reconstruction of the Herschel Pointing Jitter")
- Open work

Introduction

Herschel Startracker
512x512, f≈30mm, 117” pixel size







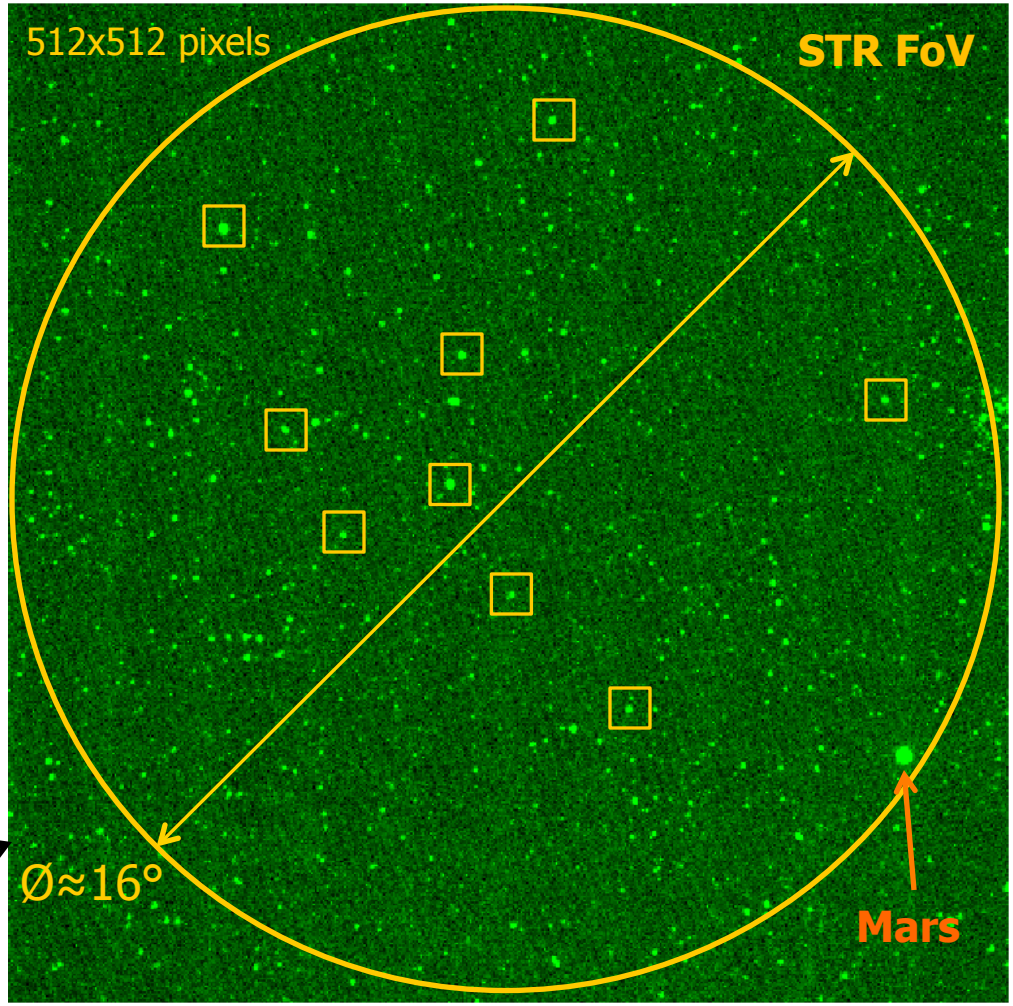
SVM with highlighted ACMS components

Attitude Determination from STR data

- STR on-board software (@4Hz):
  - Applies on-board optical distortion and relativistic aberration corrections
  - Selects, identifies (by on-board star catalog) and tracks 9 stars in the field (or 18 stars interlaced)
  - Centroiding is done by calculating the barycenter of each selected star on the CCD
  - Runs an algorithm to calculate the attitude in the STR reference frame

Not available from telemetry !

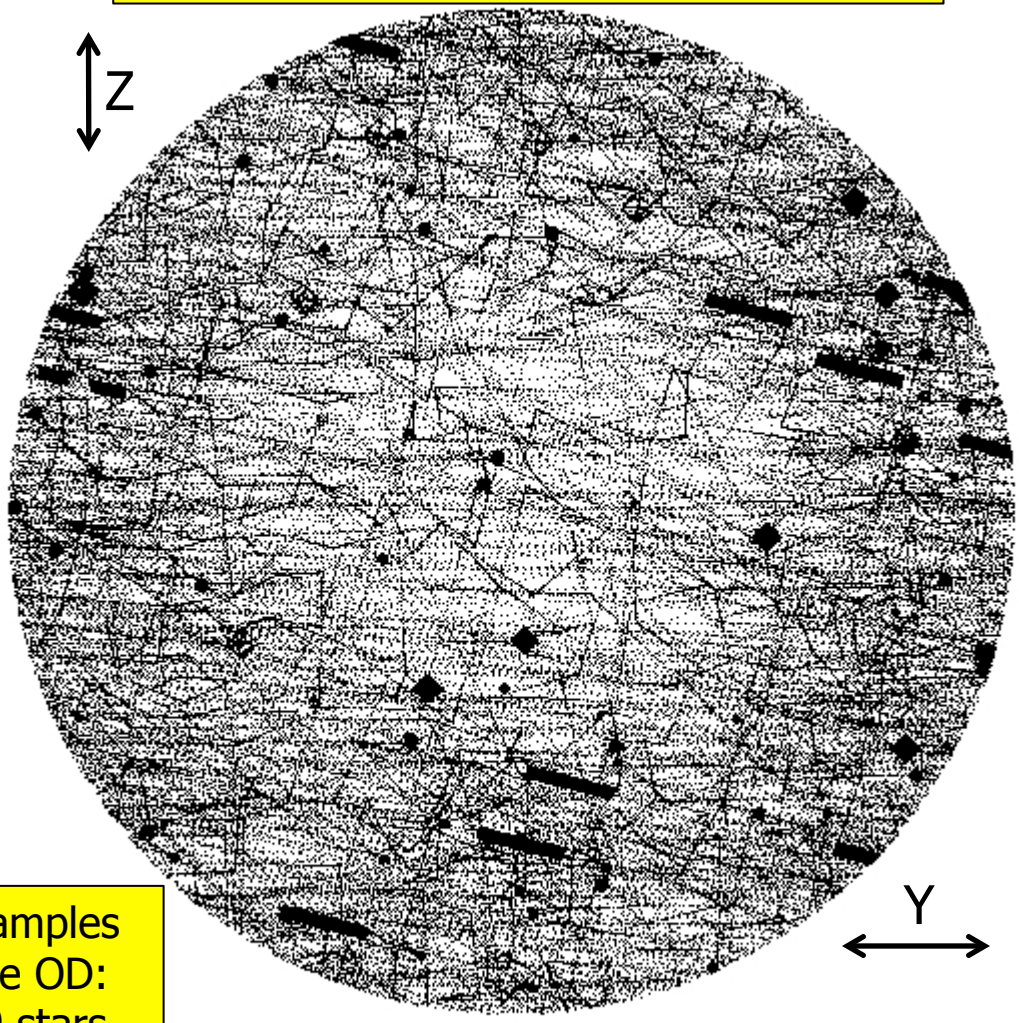
STR CCD dump taken on OD320



Attitude Determination from STR data

- Recode on-board STR attitude calculation on ground @1Hz (star-catalog, focal length values, on-board polynomial correction parameters, spacecraft velocity vectors)
- Calculated attitudes allow to re-project guide star positions onto the CCD for comparison with measured positions.
- Residuals [measured-projected] provide quality information on derived attitude, guide star quality and or residual optical distortions [dy,dz] as a function of the position on the STR FoV

OD320 STR FoV coverage (1Hz data): bary-centers for all measured guide stars

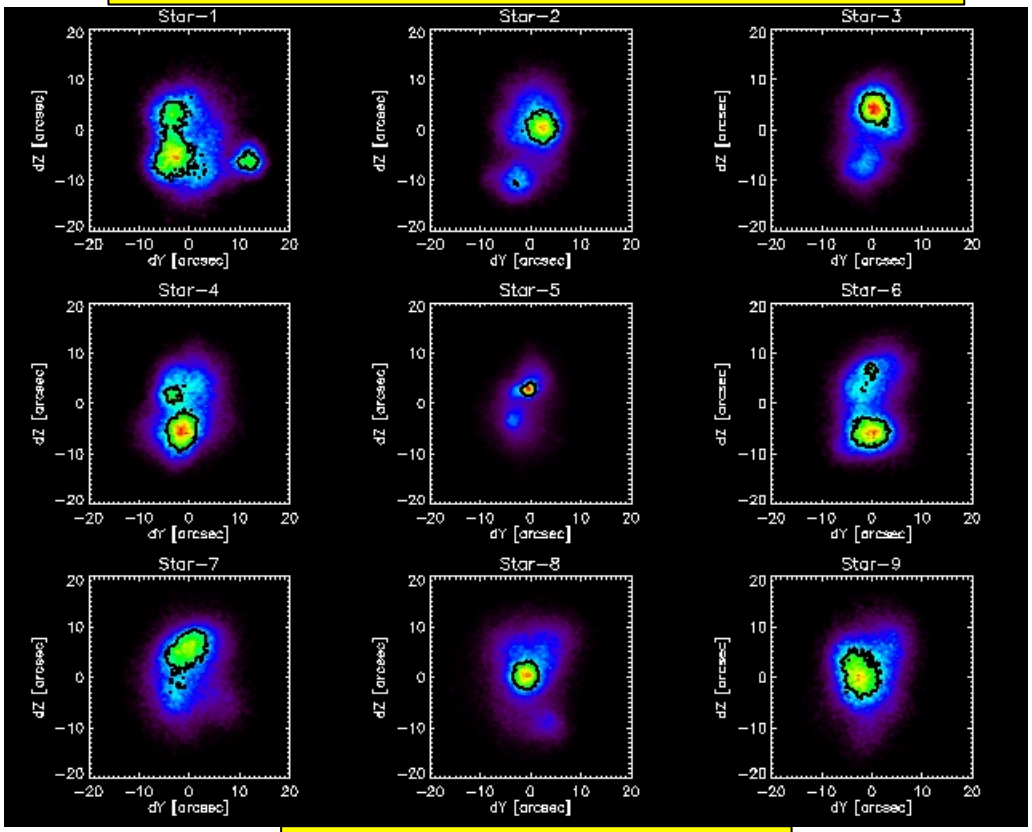


Number of samples for one entire OD: 86400sec x 9 stars

Attitude Determination from STR data

- Residuals provide [dy,dz] offsets for essentially all positions on the STR FoV.
- An OD with good (i.e. uniform) coverage of the STR FoV, or the combination of several ODs provide the remaining optical distortion after all on-board corrections
- These residual distortions are different for the different mission phases and can be expressed as 2D-Polynomials.

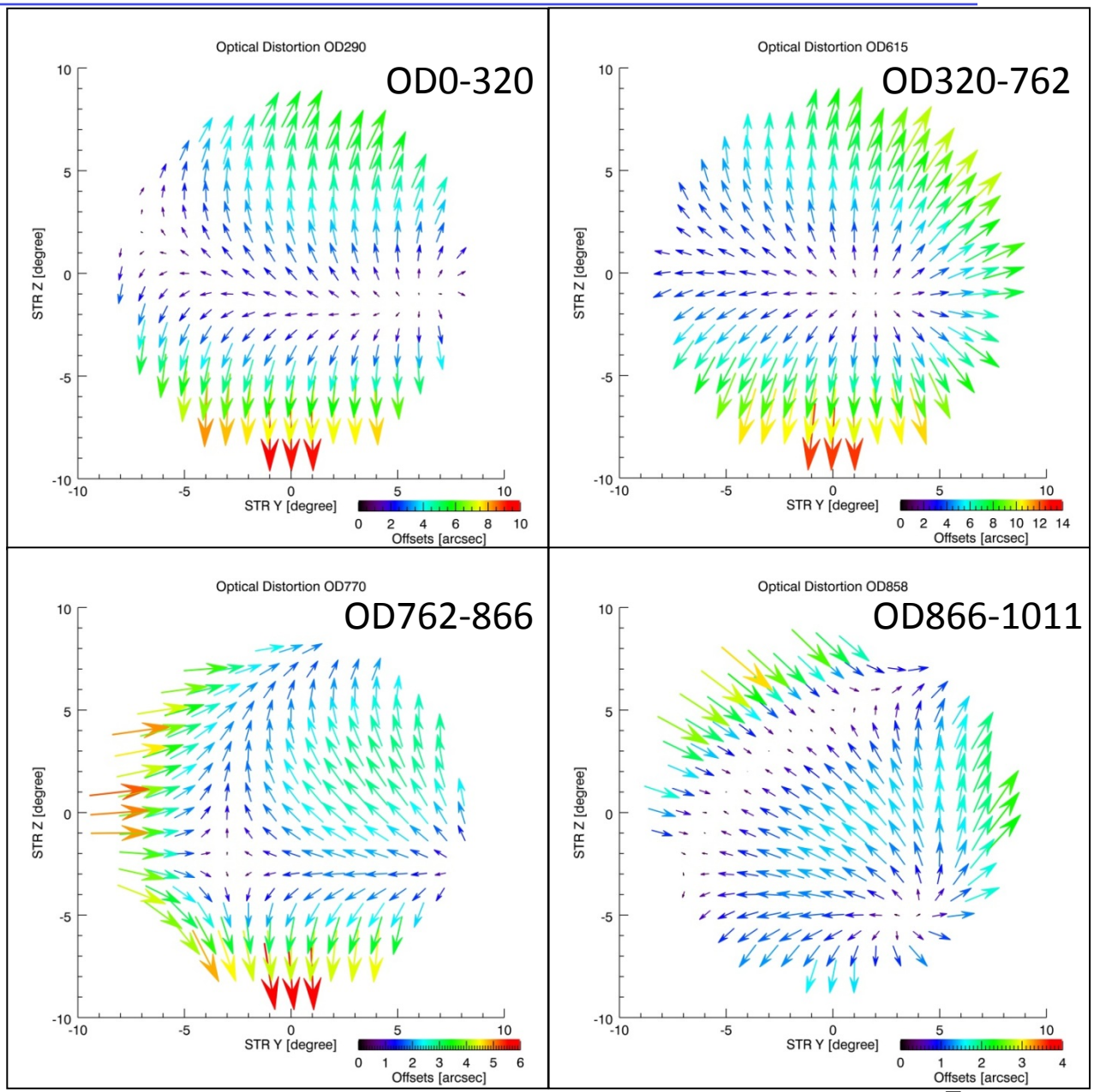
2-D Histograms of all measured guide star residuals during OD320



uncorrected, as observed

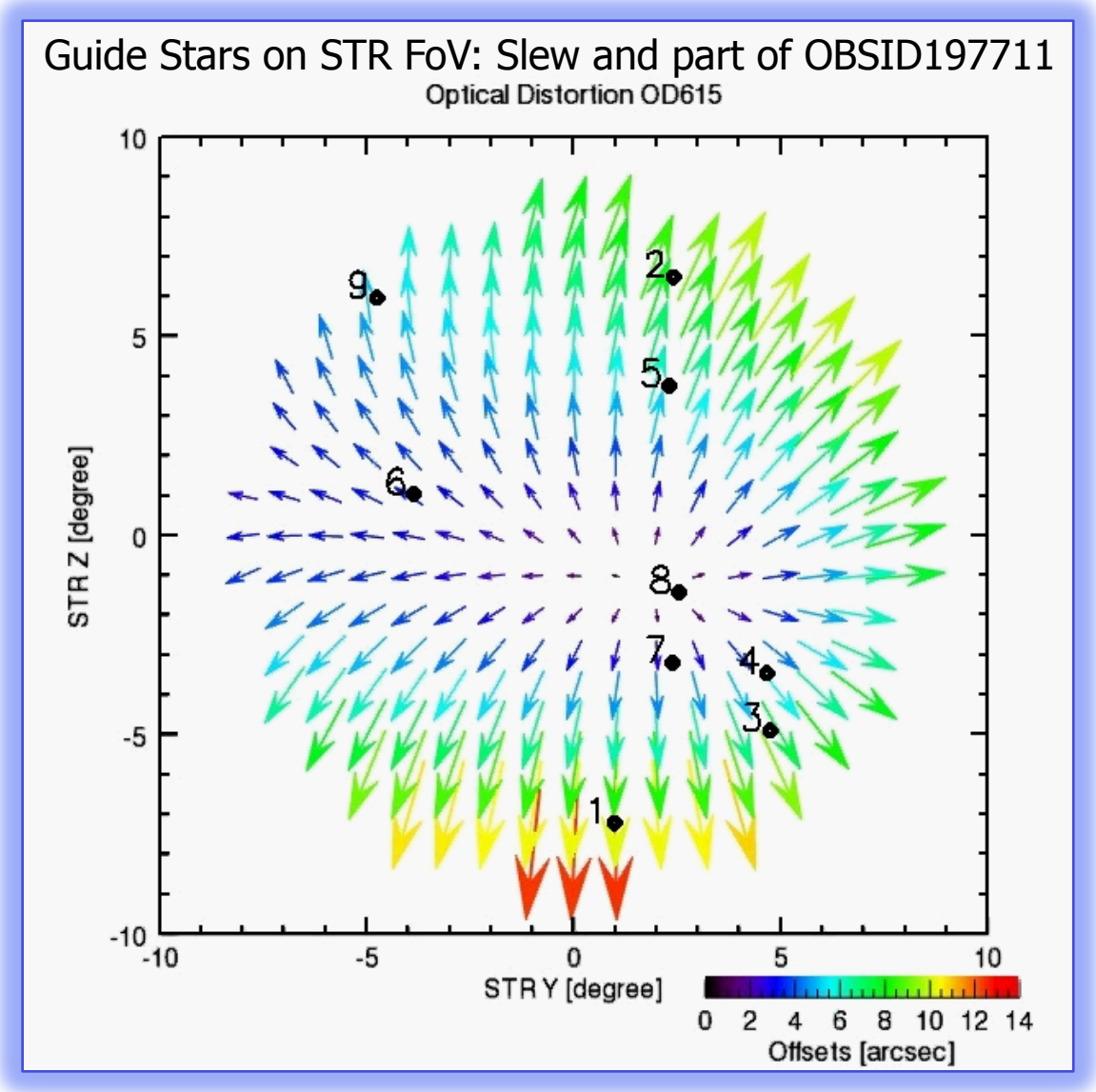
Attitude Determination from STR data

2D representation of the polynomial correction function for the 4 initial mission phases



- Change of CCD temperature from **OD320** onwards
- Update of $\mathbf{f_0}$ in **OD762**
- Update of $\mathbf{k_1}$ and $\mathbf{h_1}$ on-board polynomial coefficients from **OD866** onwards (and in **OD858**)
- Update of entire polynomial from **OD1011** onwards (and in **OD1005**)

Attitude Determination from STR data



Attitude Determination from STR data

- The star tracker on-board software has a built in 2D-polynomial optical correction of its measured star positions.

$$y_{dc} = -k_0 + k_1 y_{sc} + k_2 z_{sc} + k_3 y_{sc}\left(y_{sc}^2 + z_{sc}^2\right) + k_4 y_{sc}\left(y_{sc}^2 + z_{sc}^2\right)^2 - k_5 y_{sc}^2 - k_6 y_{sc} z_{sc} - k_7 z_{sc}^2$$

$$z_{dc} = -h_0 + h_1 z_{sc} + h_2 y_{sc} + h_3 z_{sc}\left(y_{sc}^2 + z_{sc}^2\right) + h_4 z_{sc}\left(y_{sc}^2 + z_{sc}^2\right)^2 - h_5 z_{sc}^2 - h_6 y_{sc} z_{sc} - h_7 y_{sc}^2$$

$[y_{sc}, z_{sc}]$ = measured star positions on the CCD in units of mm

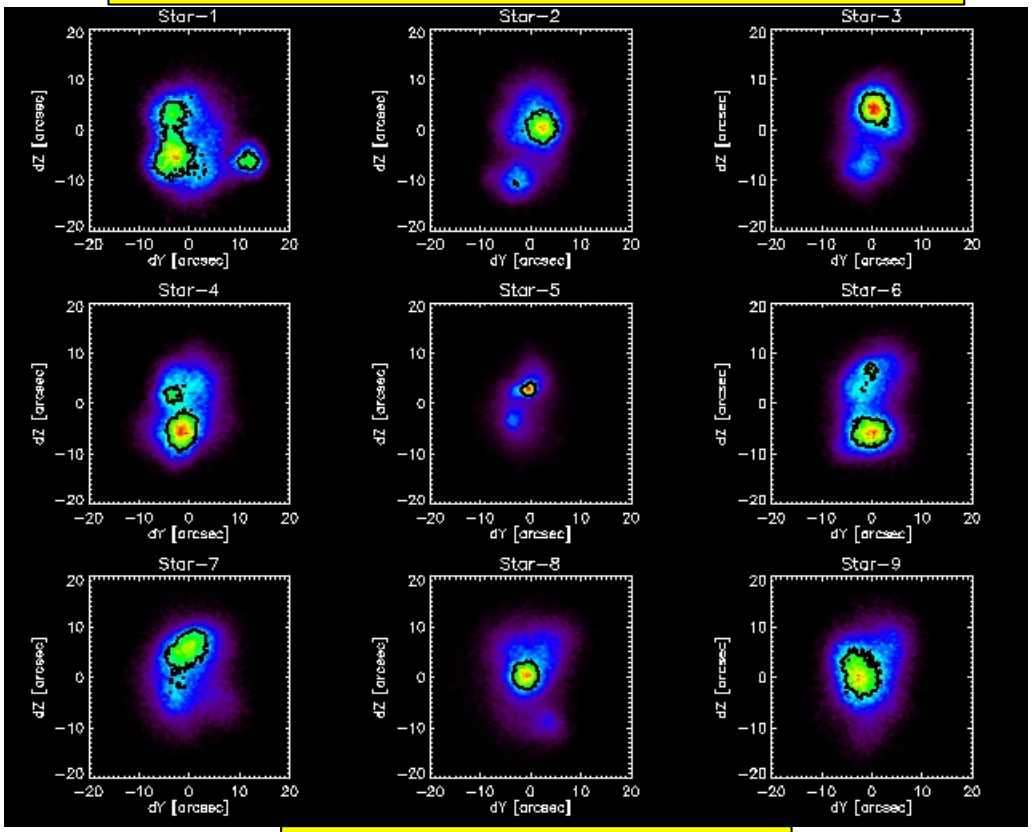
$[y_{dc}, z_{dc}]$ = distortion corrected star positions

$[h_i, k_i]$ = polynomial coefficients, for y and z respectively

Attitude Determination from STR data

- Residuals provide [dy,dz] offsets for essentially all positions on the STR FoV.
- An OD with good (i.e. uniform) coverage of the STR FoV, or the combination of several ODs provide the remaining optical distortion after all on-board corrections
- These residual distortions are different for the different mission phases and can be expressed as 2D-Polynomials.

2-D Histograms of all measured guide star residuals during OD320



uncorrected, as observed

Attitude Determination from STR data

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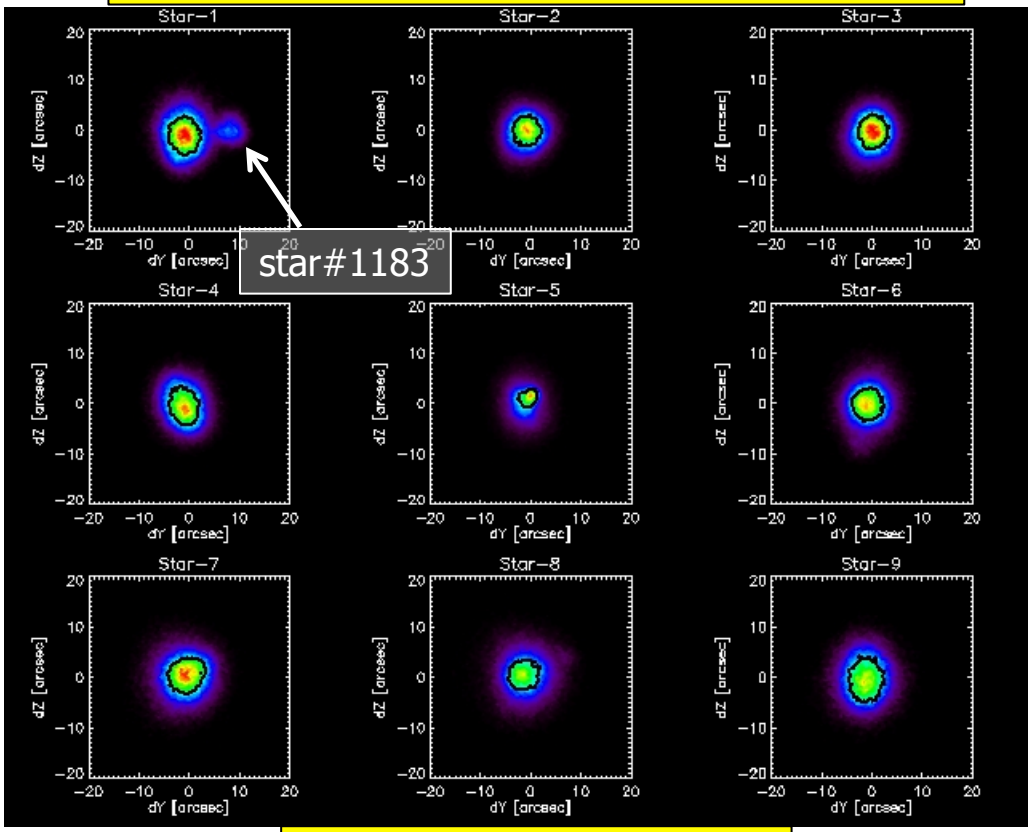


corrected, with a full 2D polynomial

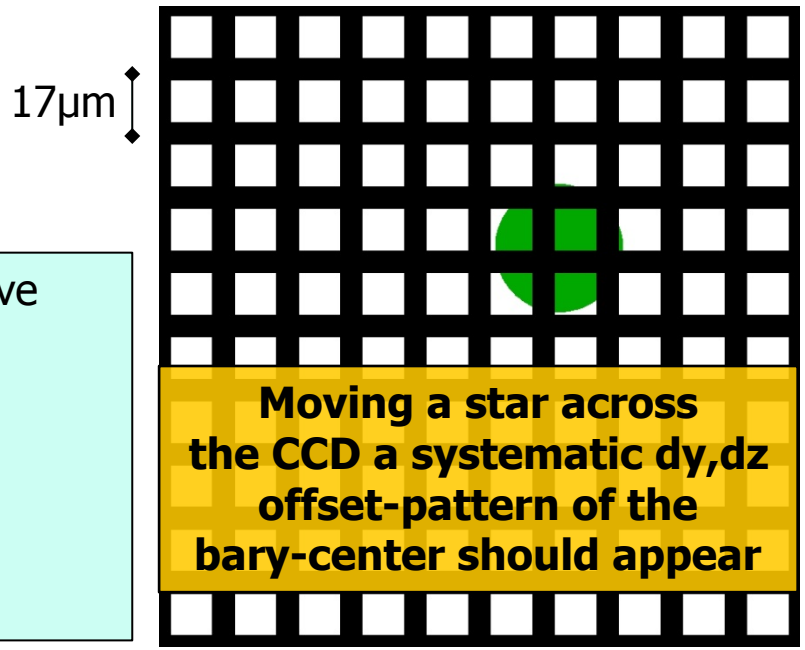
CCD Sub-Pixel Structure

- In Nov-2011 we got aware that the individual STR CCD pixels have actually some insensitive borders or gaps for radiation hardness reasons. The guess is that these gaps are as large as about 6µm. The pixel pitch = 17µm
- Insensitive pixel borders can affect the result of the guide star centroiding algorithm if they are not taken into account. On Herschel STRs they are not taken into account.
- The actual shape of the STR PSF is not known to us, may vary within the FoV and may eventually be more cylindrical shape, due to defocussing
- Centroid determination is a simple bary-center determination algorithm

Simplified illustration of sensitive vs. insensitive CCD areas:

From the ATMEL chip data sheet:
TH7890M 512x512; Pixel size 17µm x 17µm
100% Aperture **????**
400nm to 900nm spectral range
Photometric Response Non Uniformity 1%(σ)

assumed chip response layout



CCD Sub-Pixel Structure Determination

- Two different mission phases must be considered for the CCD sub-pixel determination:
  OD0000-OD0320: Initial optical distortions
  OD0321-today: Changed optical distortions due to lower CCD temperature

- For each period, measure as many as possible [dy, dz] offsets between measured star positions and their respective catalog position across the entire STR FoV (circular with radius ~4.08mm).

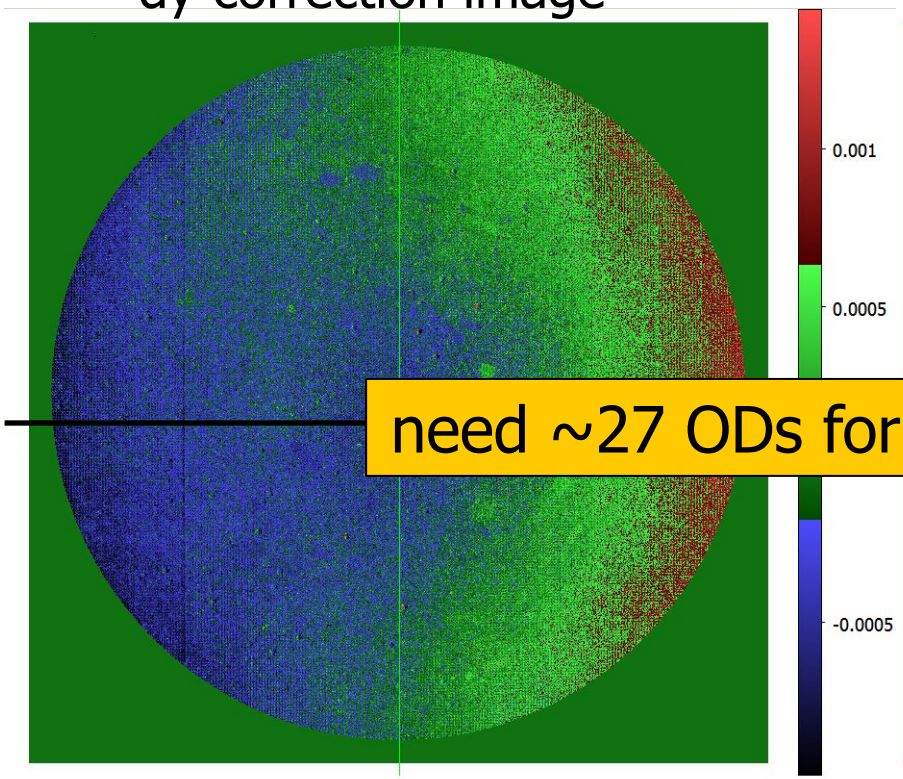
- Rebin the resulting offsets into correction images at a spatial resolution of 1/10th of an actual CCD pixel, i.e. into bins of 1.7μmx1.7μm

- The present correction images (separate for dy and dz) have been derived from the 1Hz ACMS telemetry from OD114-OD320 and OD321-OD998.

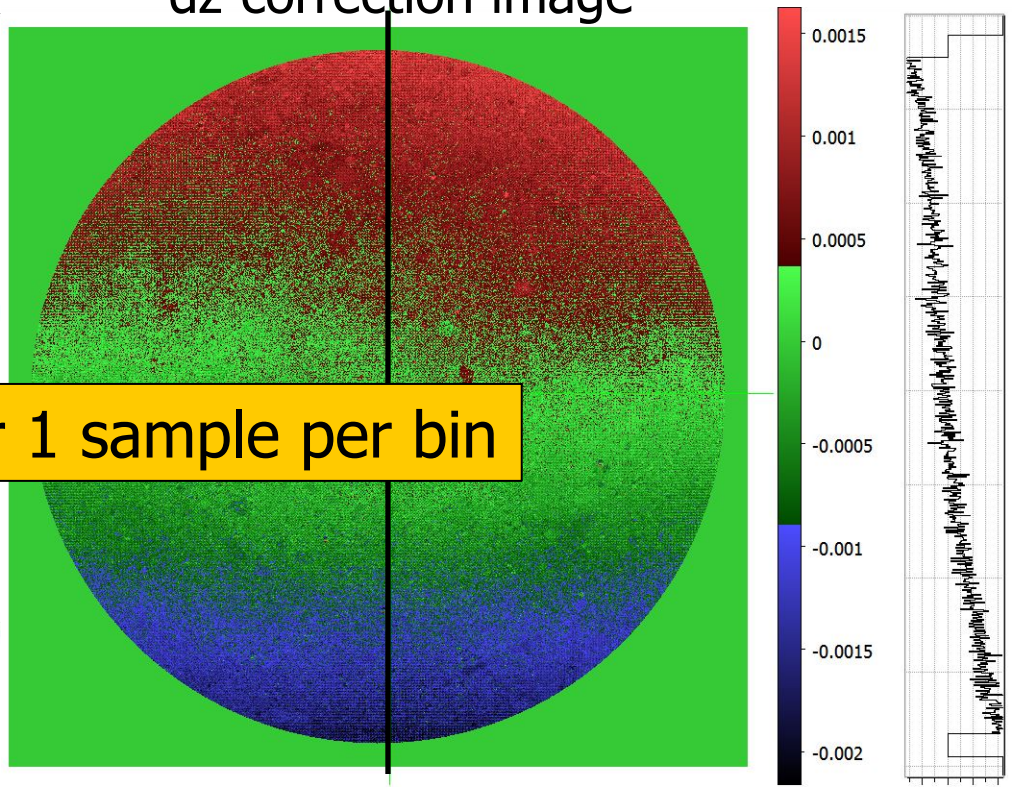
- For details of the calculations (especially given the different applied on-board polynomials) see PICC-ME-TN-041, issue 2

CCD Sub-Pixel Structure Determination

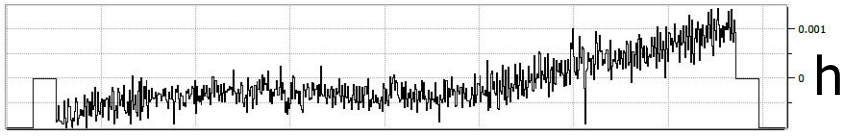
5120x5120
dy-correction image



5120x5120
dz-correction image



need ~27 ODs for 1 sample per bin



hor. cut

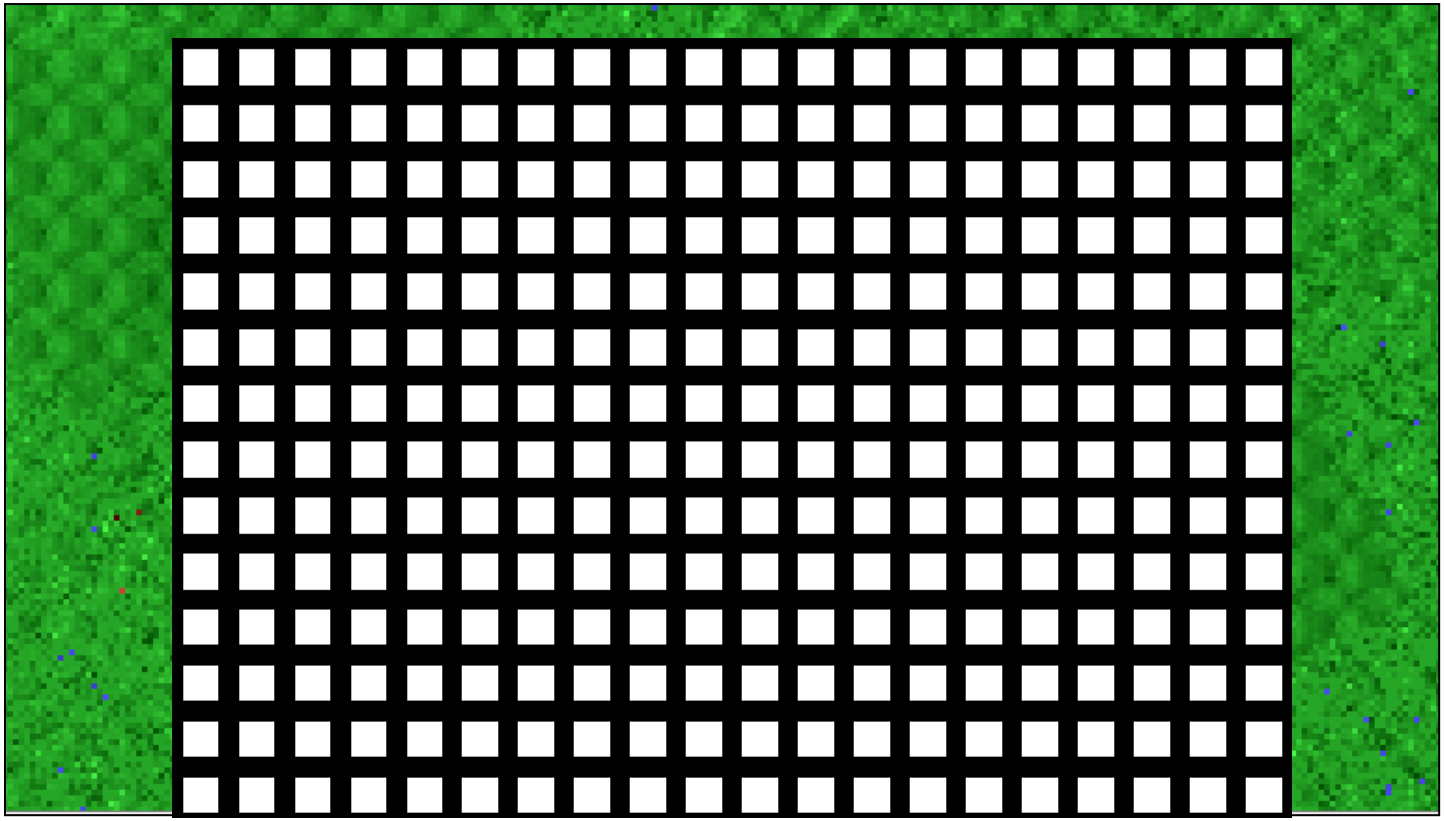
ver. cut

1μm ≈ 6.9”

CCD Sub-Pixel Structure Determination

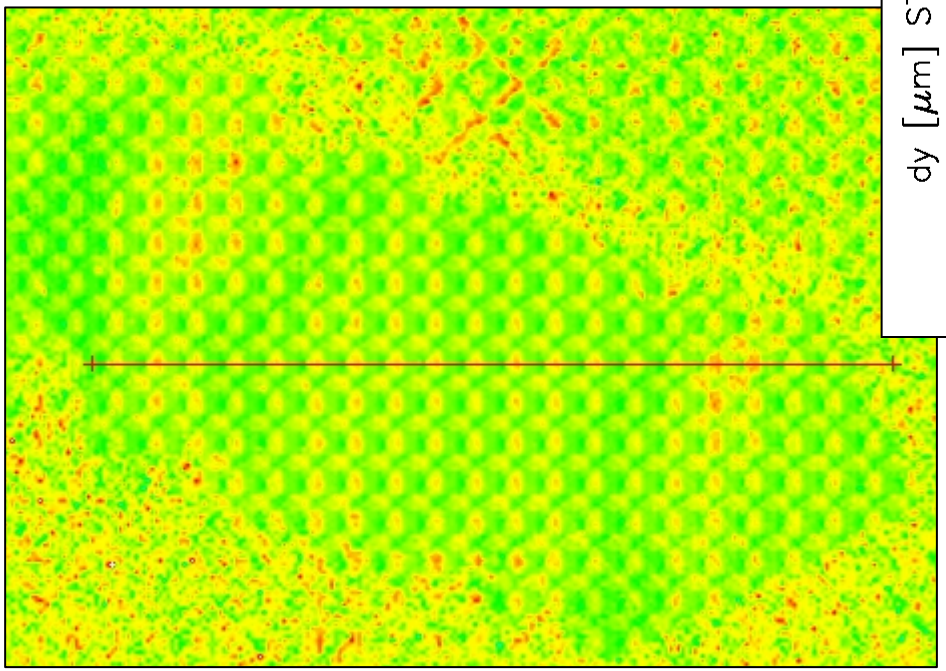
A zoom into the reconstructed [dy and dz] distortion images show indeed regular patterns compatible with the STR CCD pixel dimensions.

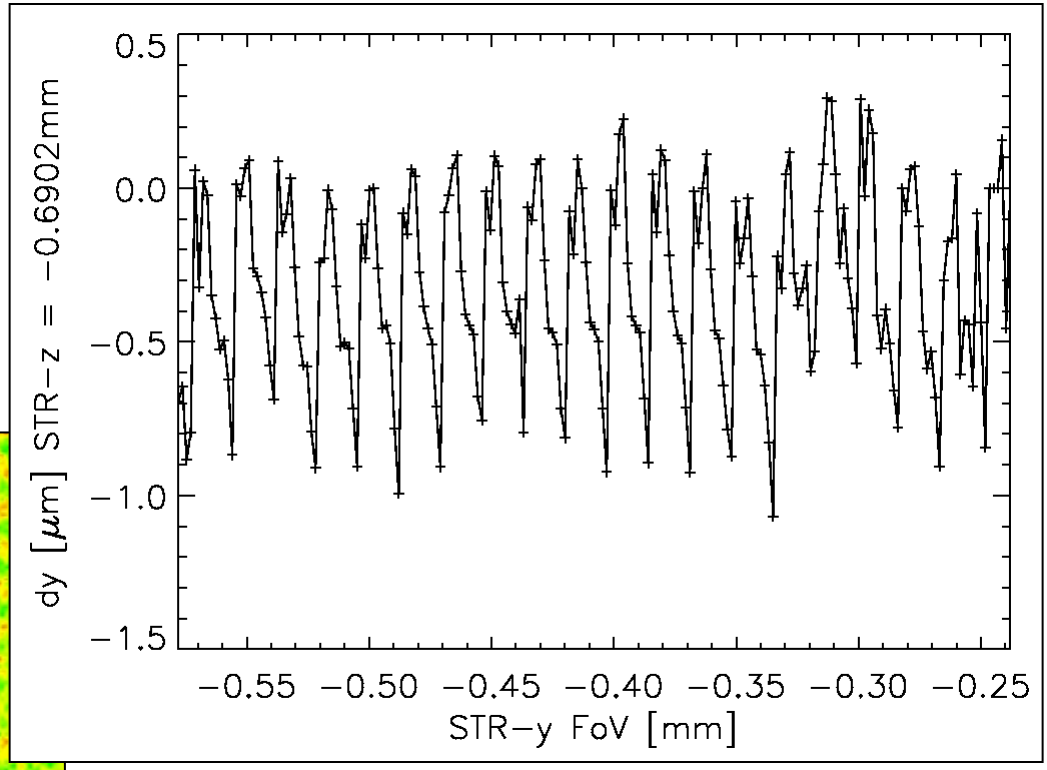
measured dy –distortion in CCD coordinates [mm] compared to regular 17µm pitch pixel pattern with 6µm insensitive gaps



CCD Sub-Pixel Structure Determination

Horizontal cut through a dy-correction image





Example:
peak-to-peak modulation ~ 1.3µm
1 STR CCD Pixel = 17µm = 116.883”

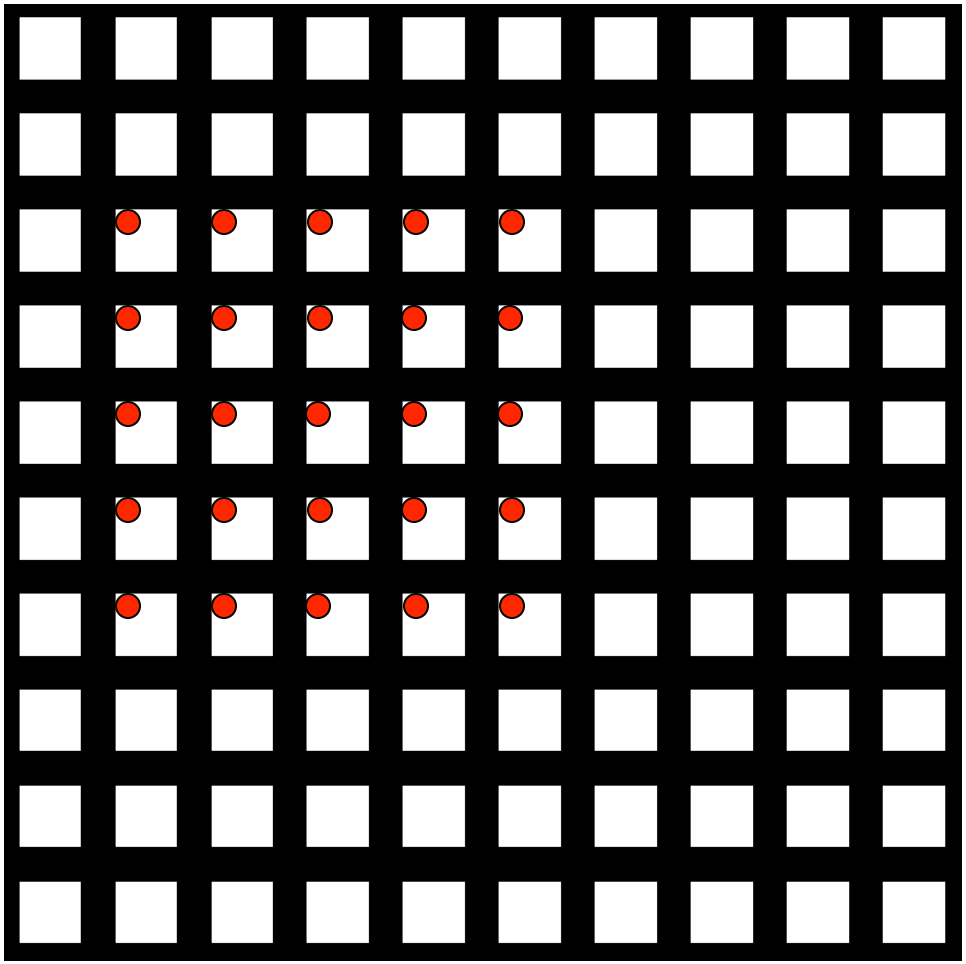
→ modulation of distortion = **8.9”**

CCD Sub-Pixel Structure Correction

- Identify the focal length and on-board polynomial coefficients which have been used for this observation
- Transform the star coordinates into the CCD reference frame
- For each star and each sample of this OBSID, interpolate the correction images onto the measured coordinates from the previous step, e.g. like:

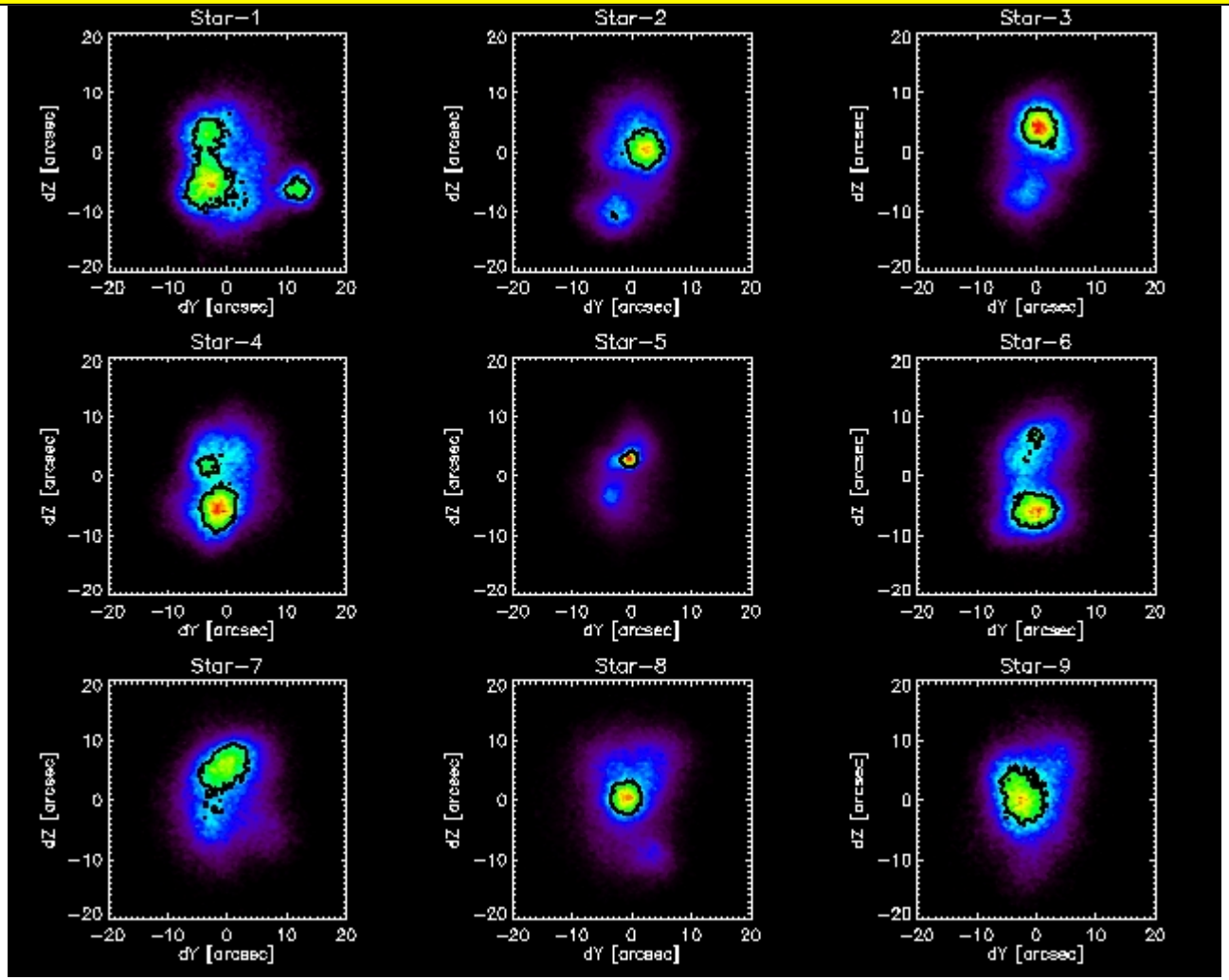
or more robust, by averaging over a nearest neighbour sample of offsets

idealized distortion pattern



Attitude Determination from STR data: Quality Check

2D Histograms of all measured guide star residuals during OD320



uncorrected,
"as observed"

Attitude Determination from STR data: Quality Check

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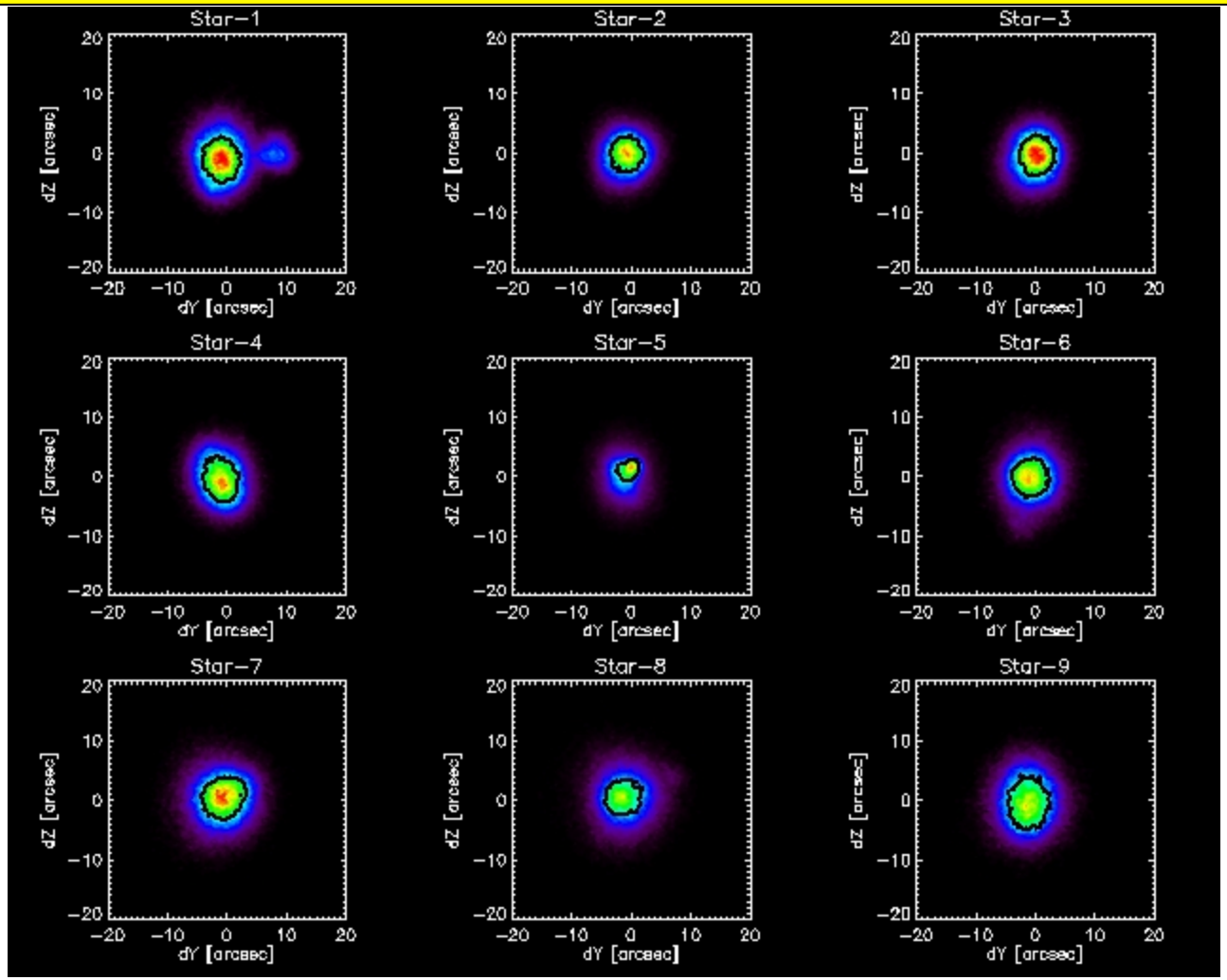
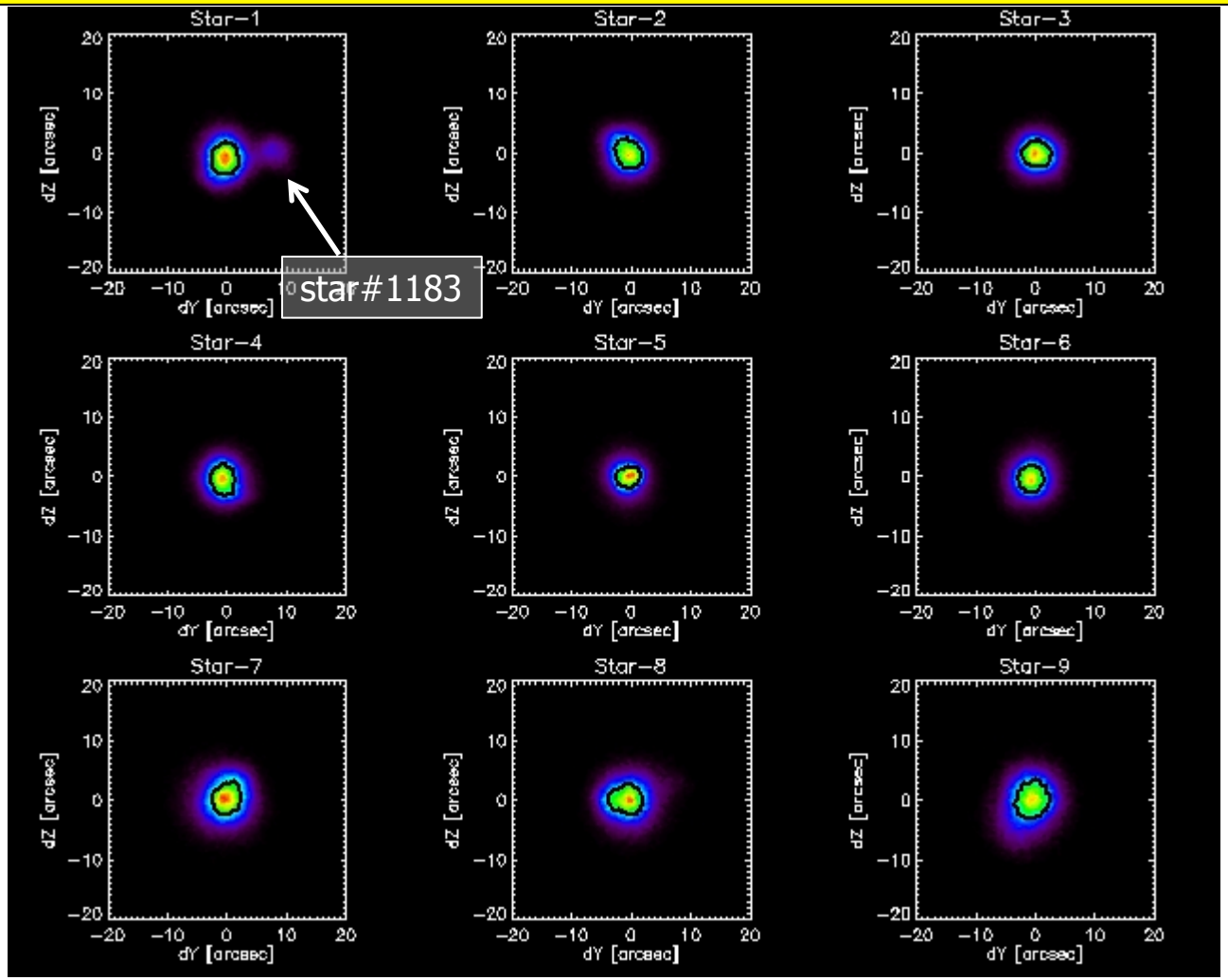


corrected, with a 2D-polynomial

Attitude Determination from STR data: Quality Check

2D Histograms of all measured guide star residuals during OD320



corrected for CCD Sub-pixel structure distortions

Bad star identification and removal

- The determination of residual star position offsets has been studied for 440 ODs (321-761) with consistent optical distortion correction (2D polynomial)
- For each star which has been used by the star tracker within this period, the following entries are stored:
  - Number of measured samples (only taken from 1Hz ACMS packets)
  - Number of different ODs on which the star has been used
  - Proper motion of the star from "A first look into the STR catalog", 27-July-2011, H. Aussel
    (Note: the on-board guide star catalog epoch is 31-Oct-2008)
  - The three flags from the same document (1=dubious position, 2 = high proper motion, 3 = barycentre offset expected)
  - [dy, dz] residuals
  - 2D-gaussian fit results
  - Median of distribution in y and z
- For each star a 2D-histogram on all samples within ±40" with a bin size 0f 0.25"x0.25" is computed

Bad star identification and removal

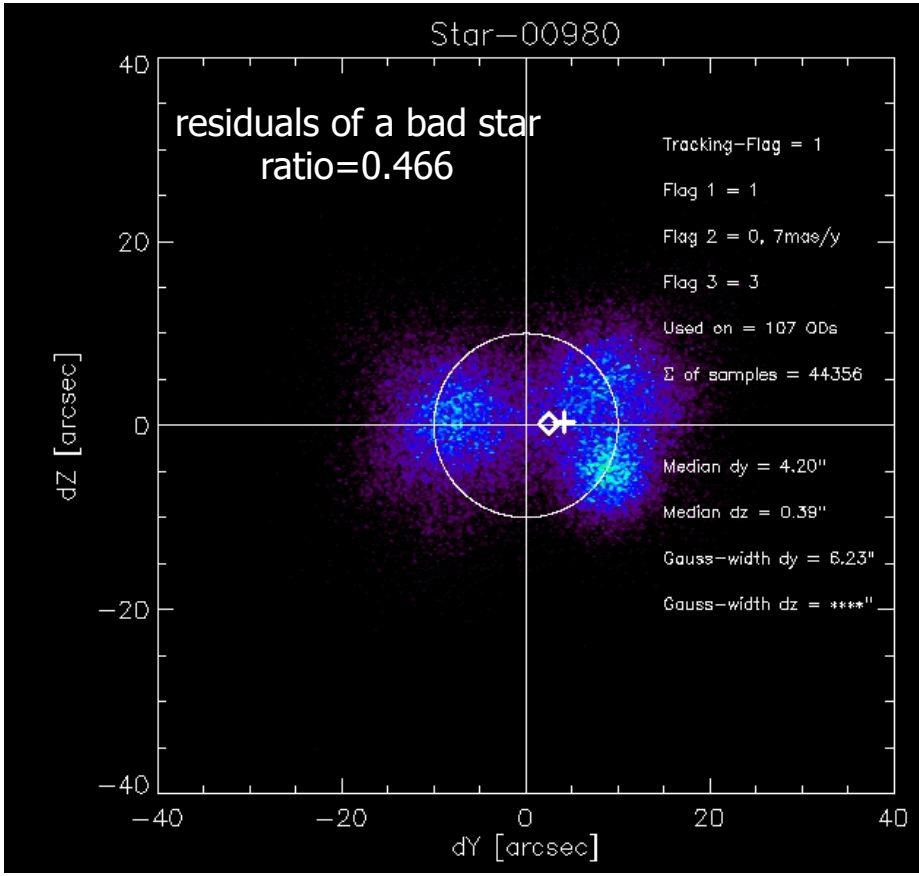
- All stars with a distribution containing less than a threshold of 80% within a radius of 10 arcsec around zero have been chosen for removal.
- The 2D-histogram statistics for all stars combined gave a 1σ in y of 3" and 1σ in z of 3.4". The 10" radius (originally just an arbitrary choice) appears to be actually very close to a 3σ selection boundary.

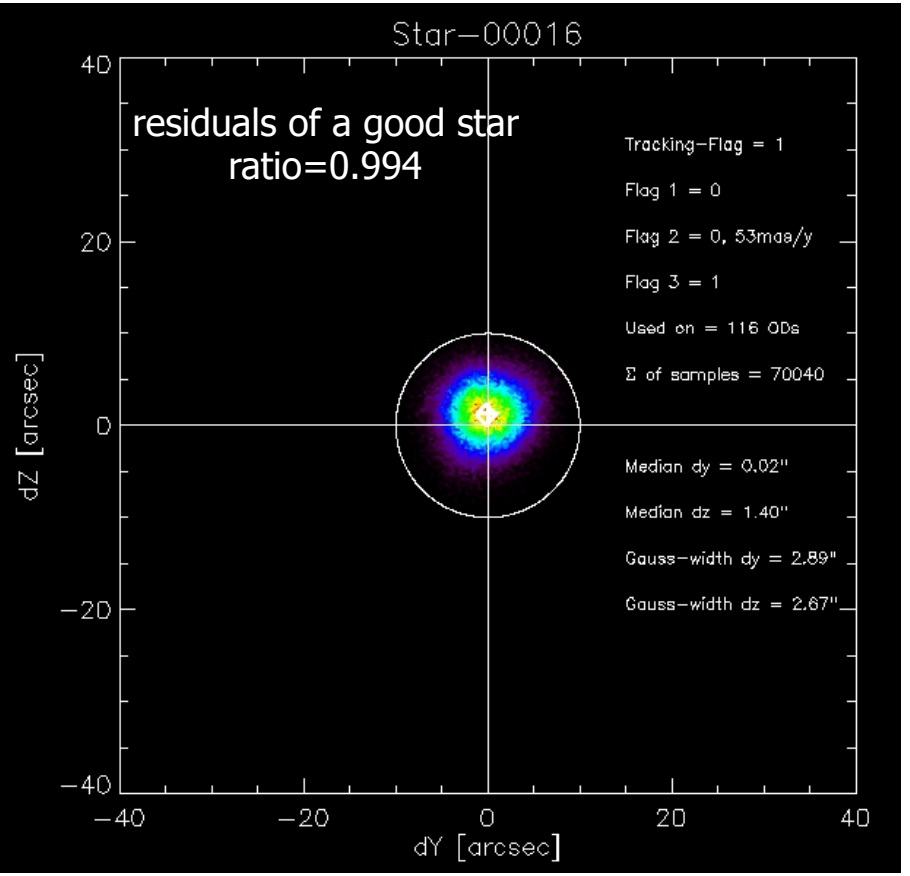
- The resulting list of 76 stars has been forwarded to industry for inspection
  → 3 out of the 76 stars have been found to be in under-populated sky regions and for those a removal from the catalogue would not result in an improvement.

- The on-board star catalogue has been patched on OD1032, such that the tracking flag is now zero for above 73 stars. The stars may still be used for attitude acquisition.

Bad star identification and removal

- In summary all stars from the on-board catalogue with tracking flag = 1 have been measured for a reasonable amount of time on several to many ODs in the mission period OD0321-OD0761. After application of a full 2D-polynomial STR FoV correction the deviations against their projected catalogue positions are used as a measure of their quality.





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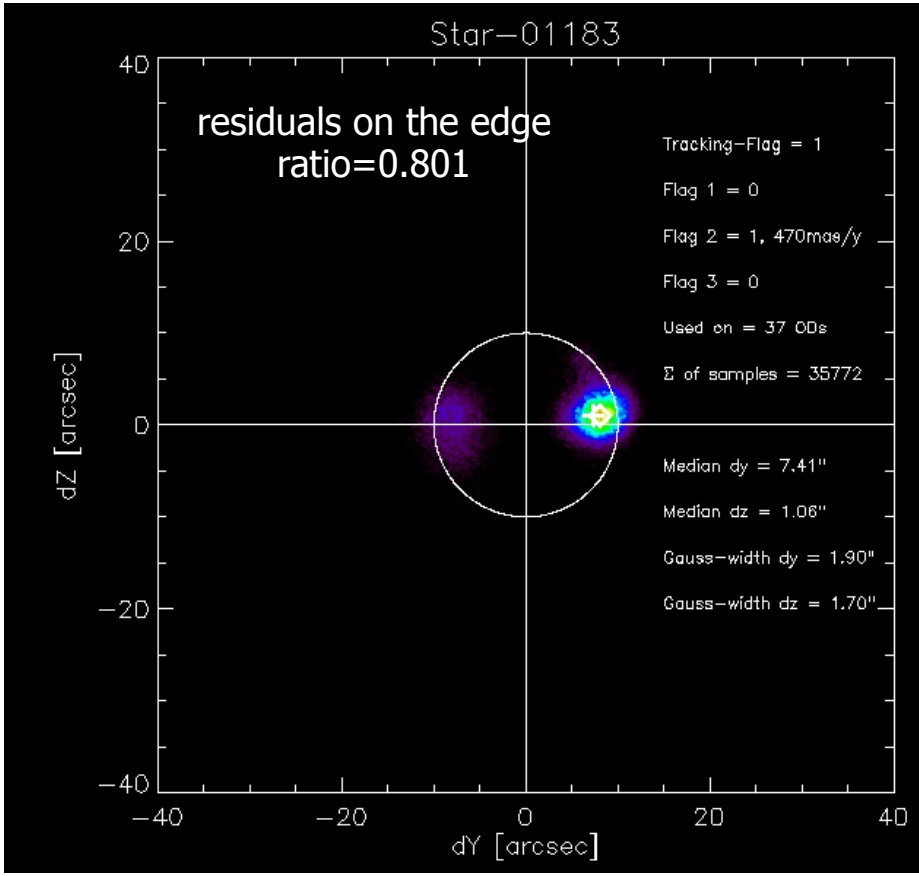
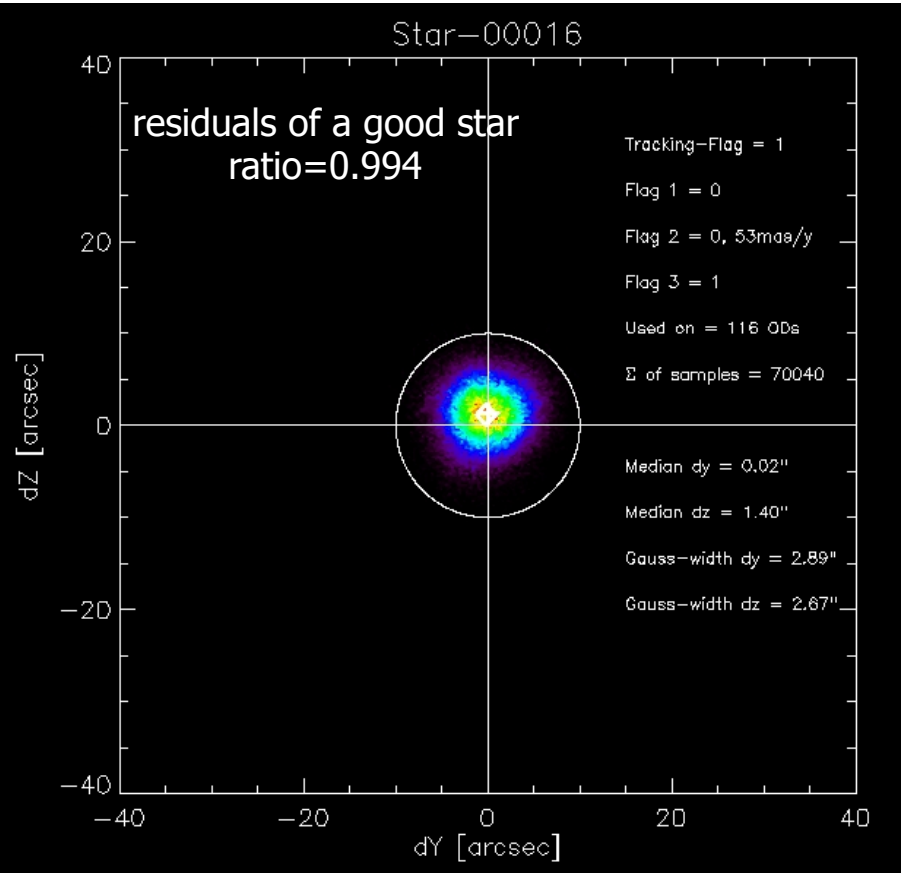


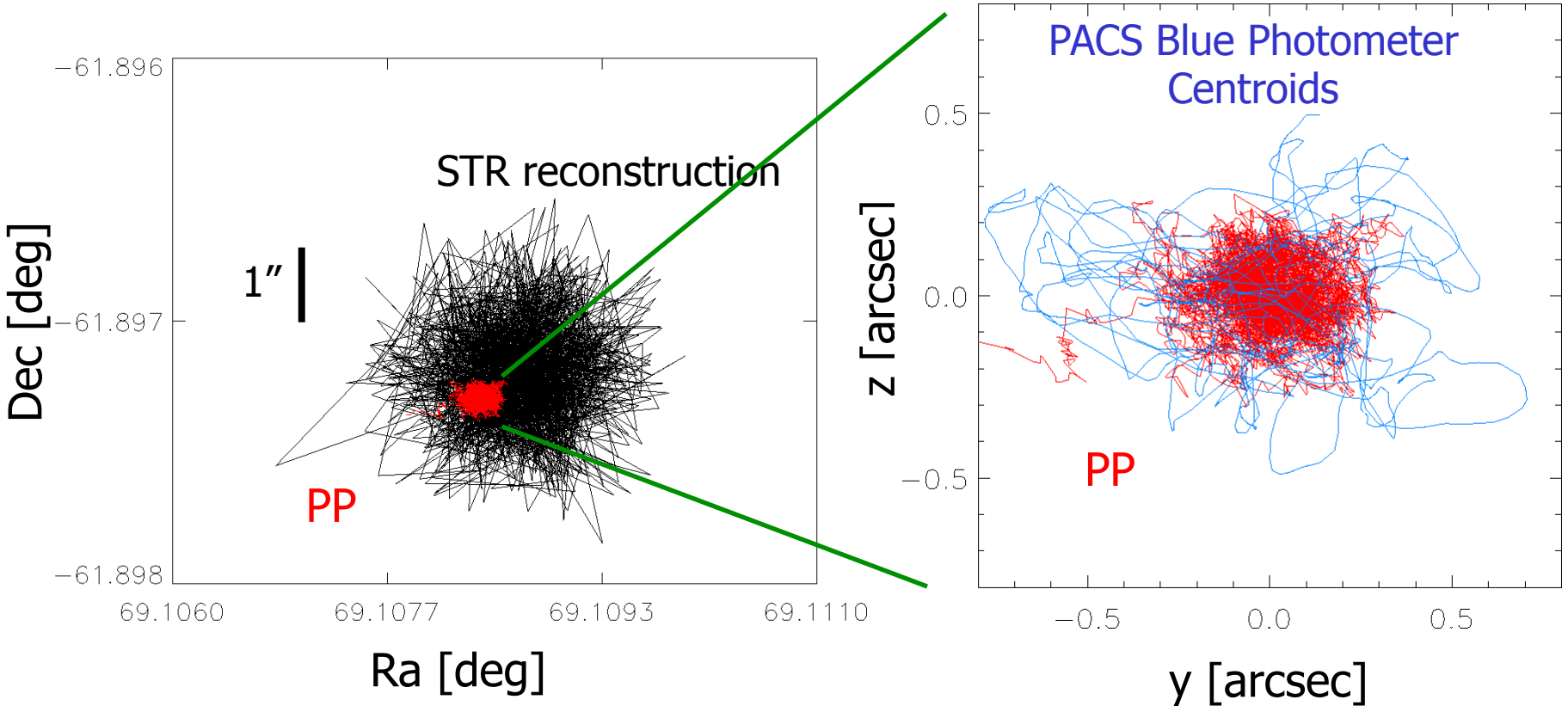


Reconstruction of the spacecraft pointing jitter

- Why is this important ?
  - Improve Strehl-ratio in photometer observations
  - Minimize beam FWHM in photometer observations
  - Accurate determination of photometer pixel positions (see also talk by M. Nielbock), i.e. the focal plane geometry
  - Instrumental beam characterization
  - Possibility to reduce pointing induced noise in spectrometer observations
  - Helps to find a way to properly filter the corrected STR data
- Why can we do this better now compared to in-flight ?
  - We do not need to care about spacecraft safety ….
  - We can look into the future
  - We can use all 4 gyros instead of only 3

Reconstruction of the spacecraft pointing jitter

- Suppose we have done the best possible attitude reconstruction from the STR data, how can we then construct a better pointing product ? Let's look at an example: OD1109 R Dor OBSID 246173

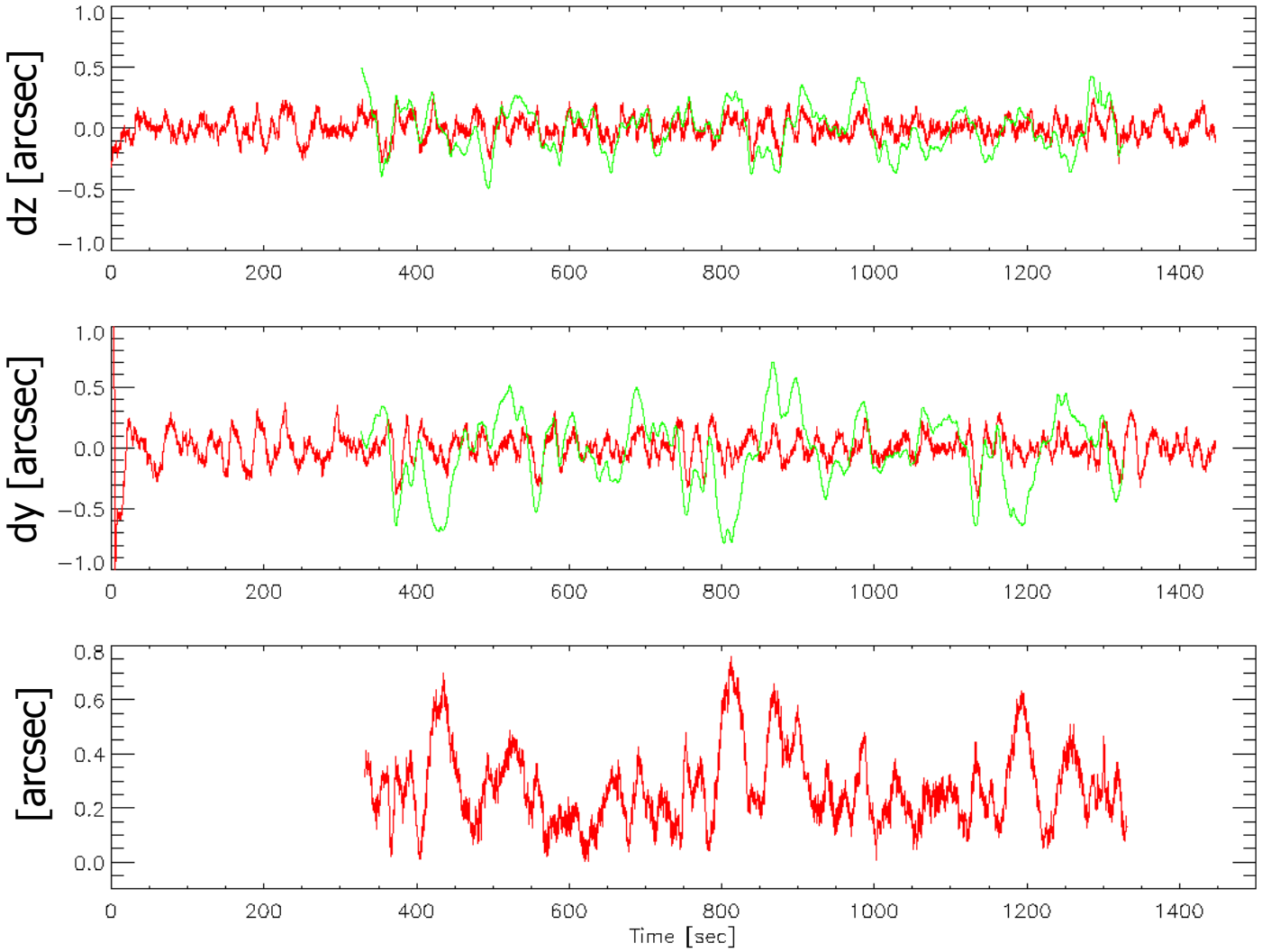


Reconstruction of the spacecraft pointing jitter

green:
centroid fits on blue PACS bolometer array

red:
Pointing product from HSA

deviation:
sqrt(dy^2+dz^2)



Northrop Grumman: Space Inertial Reference Unit

single gyro

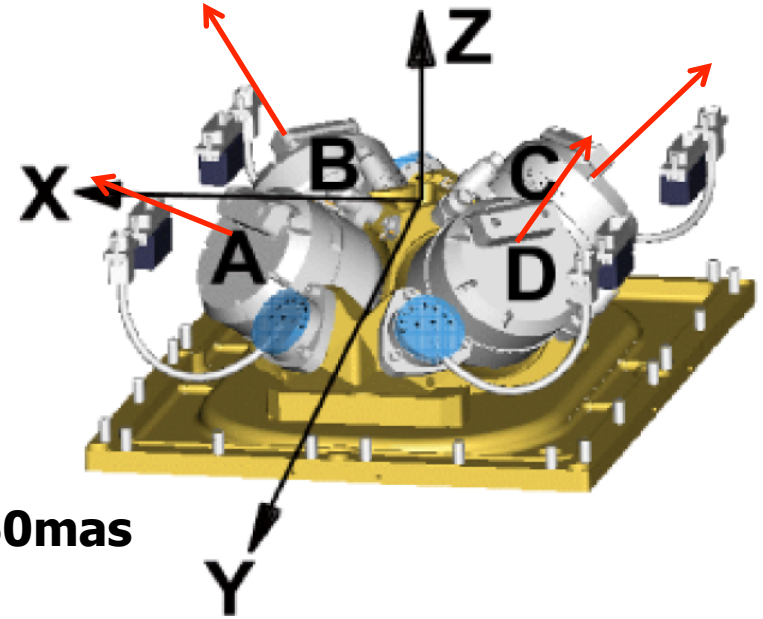
$v_{ACA} = \mathbf{A} \times g$

linear transformation coefficients are calculated from meta-data in ACMS product

$$\begin{pmatrix} X_{sc} \\ Y_{sc} \\ Z_{sc} \end{pmatrix} = \begin{pmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \end{pmatrix} \times \begin{pmatrix} g_A \\ g_B \\ g_C \\ g_D \end{pmatrix}$$

from ACMS product:
Gyr A int angle
Gyr B int angle
Gyr C int angle
Gyr D int angle

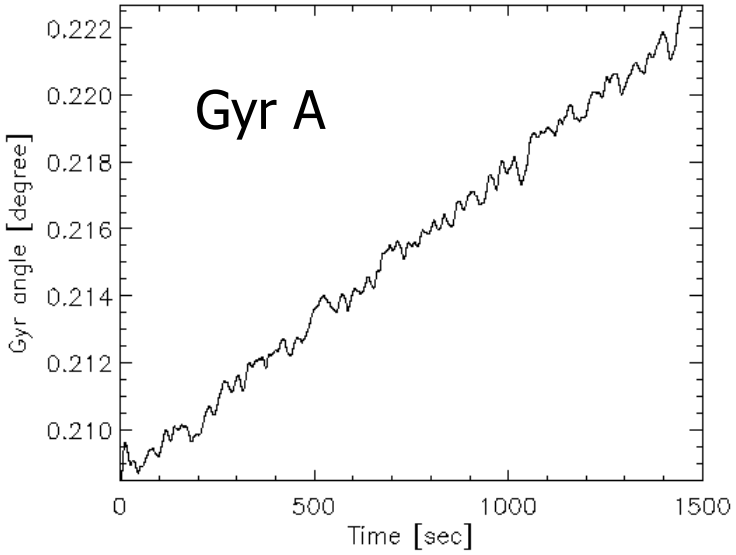
Only gyros A, B, C are used for on-board attitude filtering, on ground we can use all four !

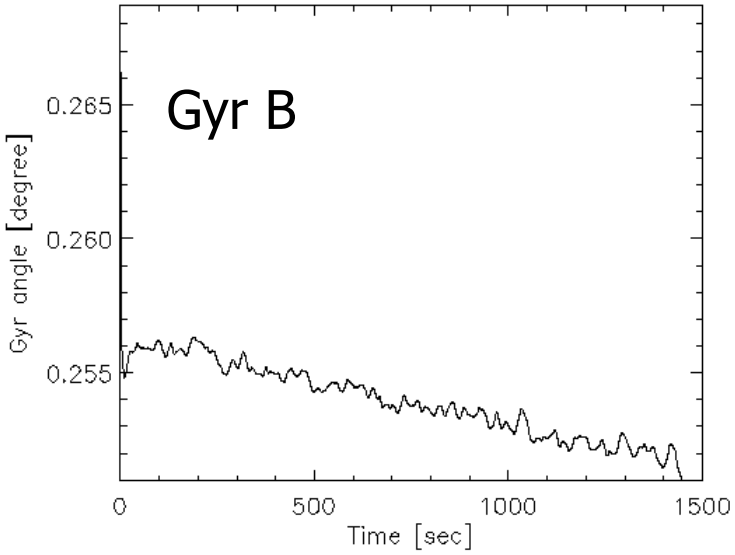


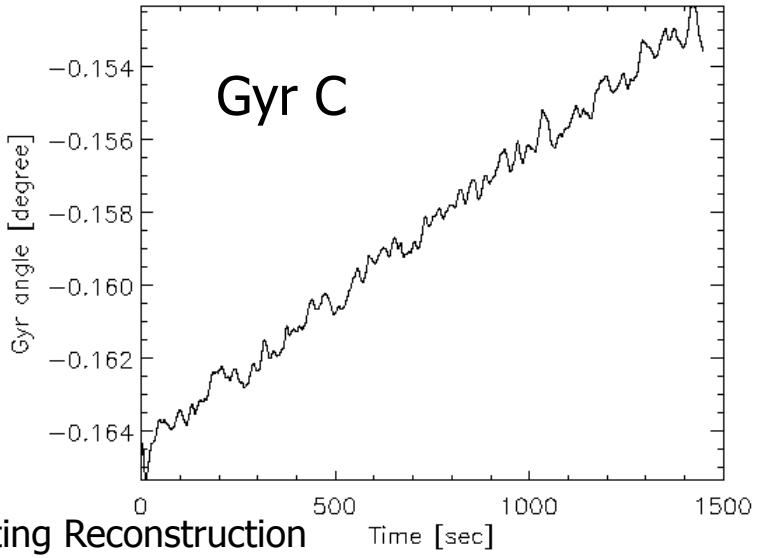
Gyro position readout: **1bit = 50mas**

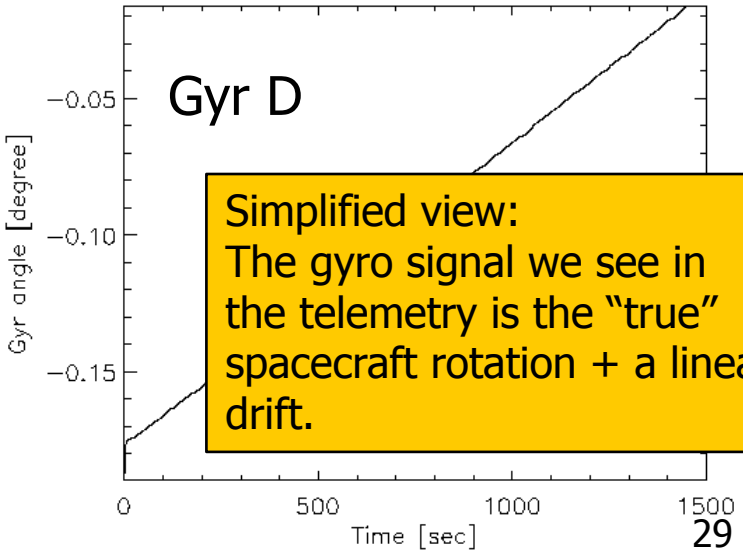
Reconstruction of the spacecraft pointing jitter

OD1109 R Dor OBSID 246173









Simplified view:
The gyro signal we see in the telemetry is the "true" spacecraft rotation + a linear drift.

Reconstruction of the spacecraft pointing jitter

- The transformation between [ga, gb ,gc ,gd] is linear, therefore the drift can be also fitted in [X, Y, Z] spacecraft coordinates.

After transformation to spacecraft coordinates:

$X_{sc}(t) = X_{gyr}(t) + X_0 + k_x \cdot t$
$Y_{sc}(t) = Y_{gyr}(t) + Y_0 + k_y \cdot t$
$Z_{sc}(t) = Z_{gyr}(t) + Z_0 + k_z \cdot t$

Fit 6 parameters:
X_0, Y_0, Z_0, k_x, k_y, k_z
to CCD sub-pixel corrected STR data [X_{STR}, Y_{STR}, Z_{STR}]

For each 4Hz gyro vector sample:

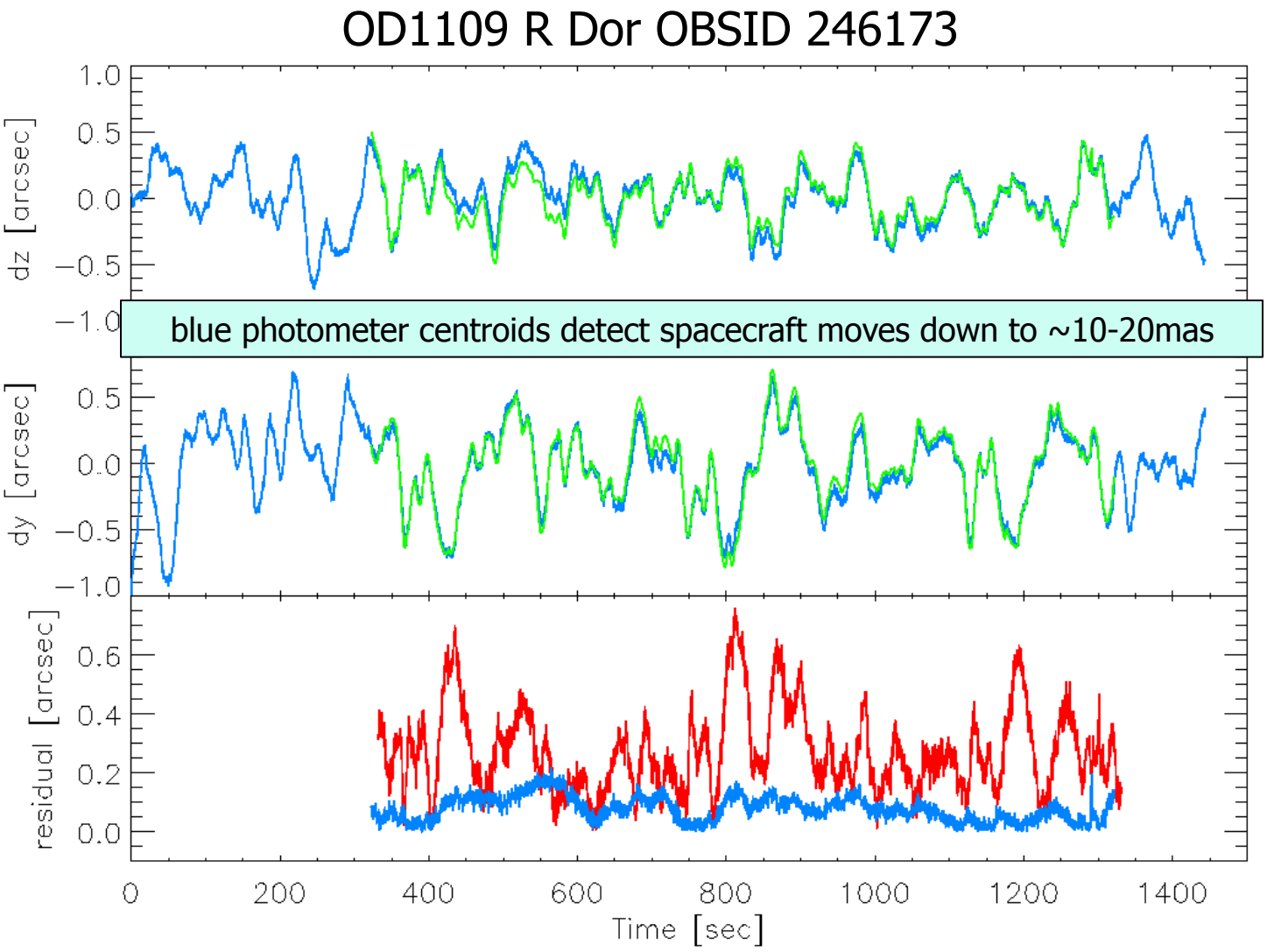
- Run least squares minimization by correcting each spacecraft vector component with a linear drift in a ±200sec time window around the sample and search X_0, Y_0, Z_0 in order to best match the reconstructed spacecraft vector timeline (of this same time interval) to the 1Hz corrected STR data (interpolated to 4Hz).
- For practical purposes the 6 parameters are only calculated in intervals of 25 seconds. Parameter values in between are obtained by linear interpolation.

Reconstruction of the spacecraft pointing jitter

green:
centroid fits on blue PACS bolometer array

blue:
STR+gyro reconstruction

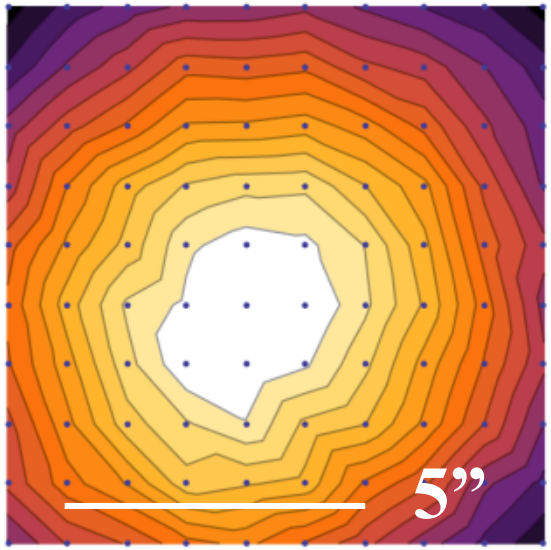
deviation:
sqrt(dy^2+dz^2)
red: PP from HSA
blue: STR+gyro reconstruction



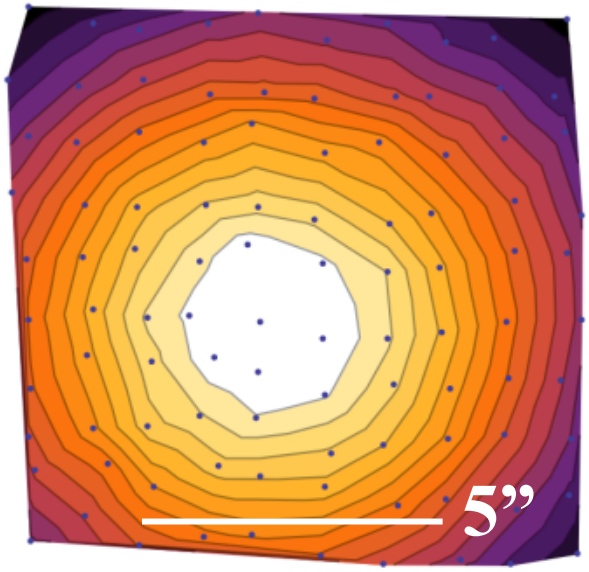
Reconstruction of the spacecraft pointing jitter

Example application: PACS Spectrometer beam measurement on Neptune

as reported in PP



corrected



Status and Open/Future Work

- The STR CCD Sub-Pixel correction code has been translated into HIPE and adapted to work with the ACMS and TCHIST products (by **Bart Vandenbussche (KUL)** → delivered to HSC 8-Mar-2013)
- Coding/translation of the Gyro-part into HIPE is in progress

- Update the correction images with ACMS information of all available ODs (at present only up to OD998) → will be done after EoHe
- Update the ACMS product to add the color coefficients of the guide stars for focal length corrections (to be done by HSC)
- Interactive tools for checking the guide star quality for individual observations ?

- The Gyro-reconstruction code so far was only an approximation for small angles (staring, mini-maps etc.). A more general approach, including slews and large maps is ready since 21-Mar-2013 and is currently under test.