Arcsecond level pointing of the H.E.S.S. telescopes

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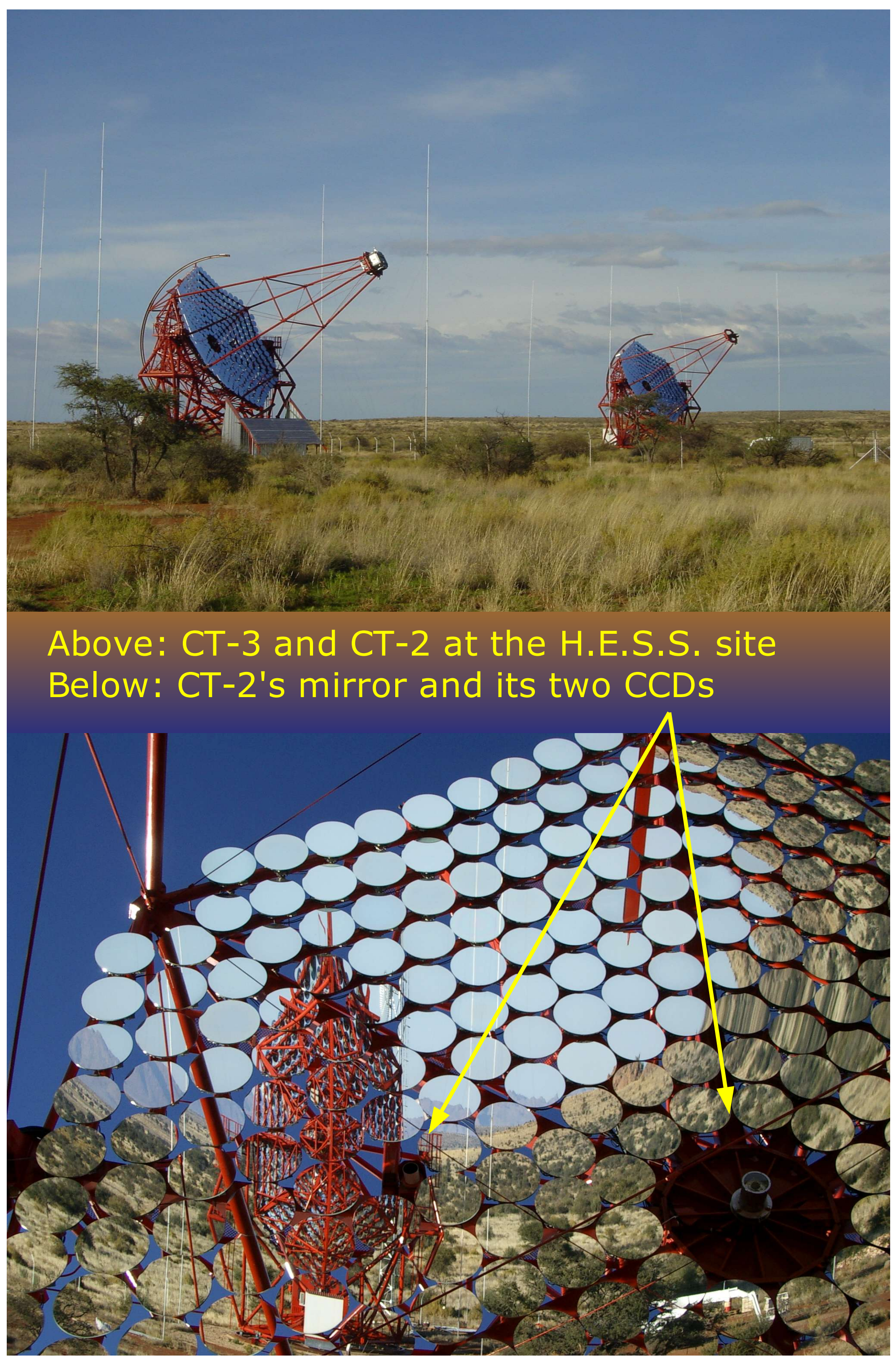
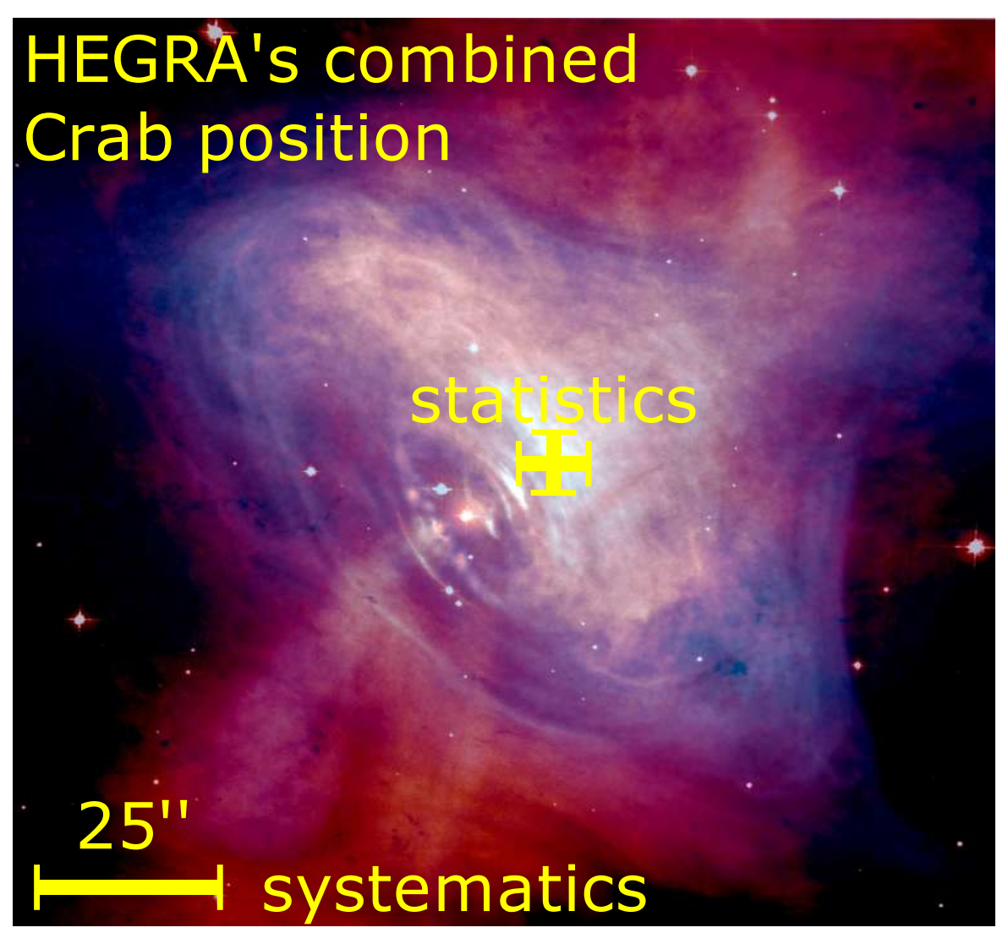
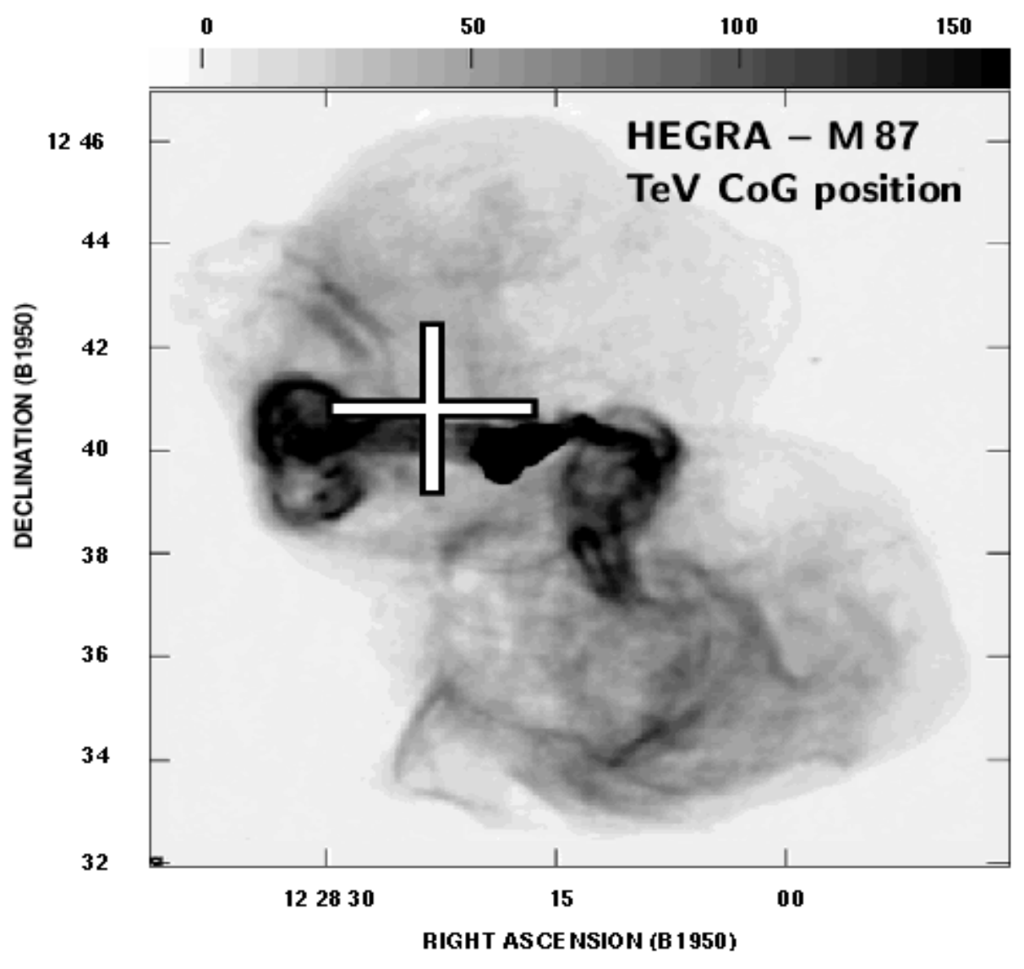

Above: CT-3 and CT-2 at the H.E.S.S. site
Below: CT-2's mirror and its two CCDs

Gamma-ray experiments using the imaging atmospheric Cherenkov technique have a relatively modest angular resolution of typically 0.05° to 0.1° per event. The centroid of a point-source emitter, however, can be determined with much higher precision, down to a few arcseconds for strong sources. The localization of the Crab TeV source with HEGRA, for example, was dominated by systematic uncertainties in telescope pointing at the 25 arcsecond level. For H.E.S.S. with its increased sensitivity it is therefore desirable to lower the systematic pointing error by a factor of 10 compared to HEGRA. As the exposure times are on a nanosecond scale it is not necessary to control actively the telescope pointing to the desired accuracy, as one can correct the pointing offline. We demonstrate that we can achieve the desired 3 arcseconds pointing precision in the analysis chain by a two step procedure: a detailed mechanical pointing model is used to predict pointing deviations, and a fine correction is derived using stars observed in a guide telescope equipped with a CCD chip.

Precise directional information for TeV sources is of astrophysical interest

Morphology, as well as spectral investigations, can help to determine the origin of TeV gamma-rays. First generation experiments were not directly able to prove that the TeV emission of the Crab nebula actually originates from the nebula and not from the pulsar. Systematic errors were too big. Similarly for the extragalactic source M87: Due to sytematics and poor statistics one could not distinguish whether the modest excess of TeV gamma-rays comes from the nucleus or the jets of the galaxy.





For a precise location of a TeV source one needs pointing corrections

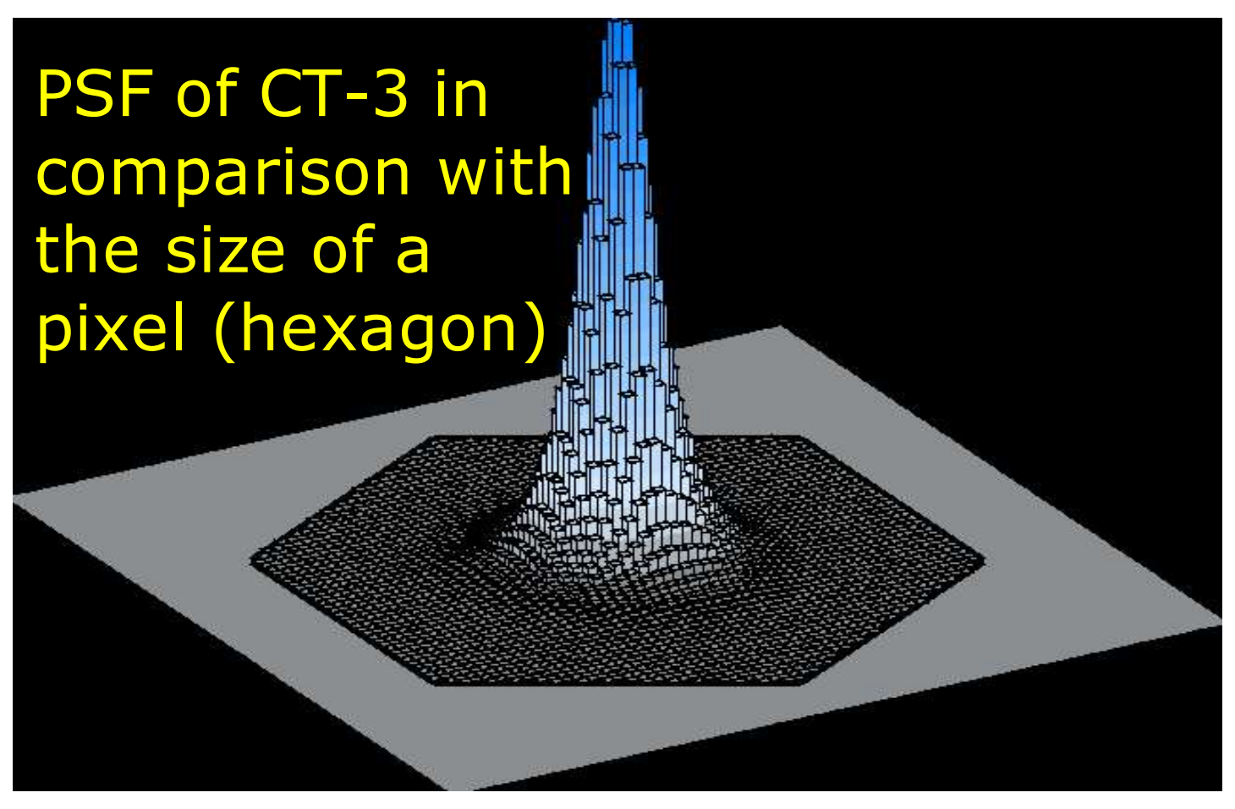
The precision with which astrophysical sources can be located is determined by two factors.

- Statistics: Eventwise the direction resolution is typically 300''. However, one can determine the centroid of a point-source emitter to much higher precision. For strong sources a few arcseconds can be reached.
- Systematics: Any telescope shows a mis-pointing due to mechanical imperfections. The H.E.S.S. telescopes are mechanically precise to the 60'' level.

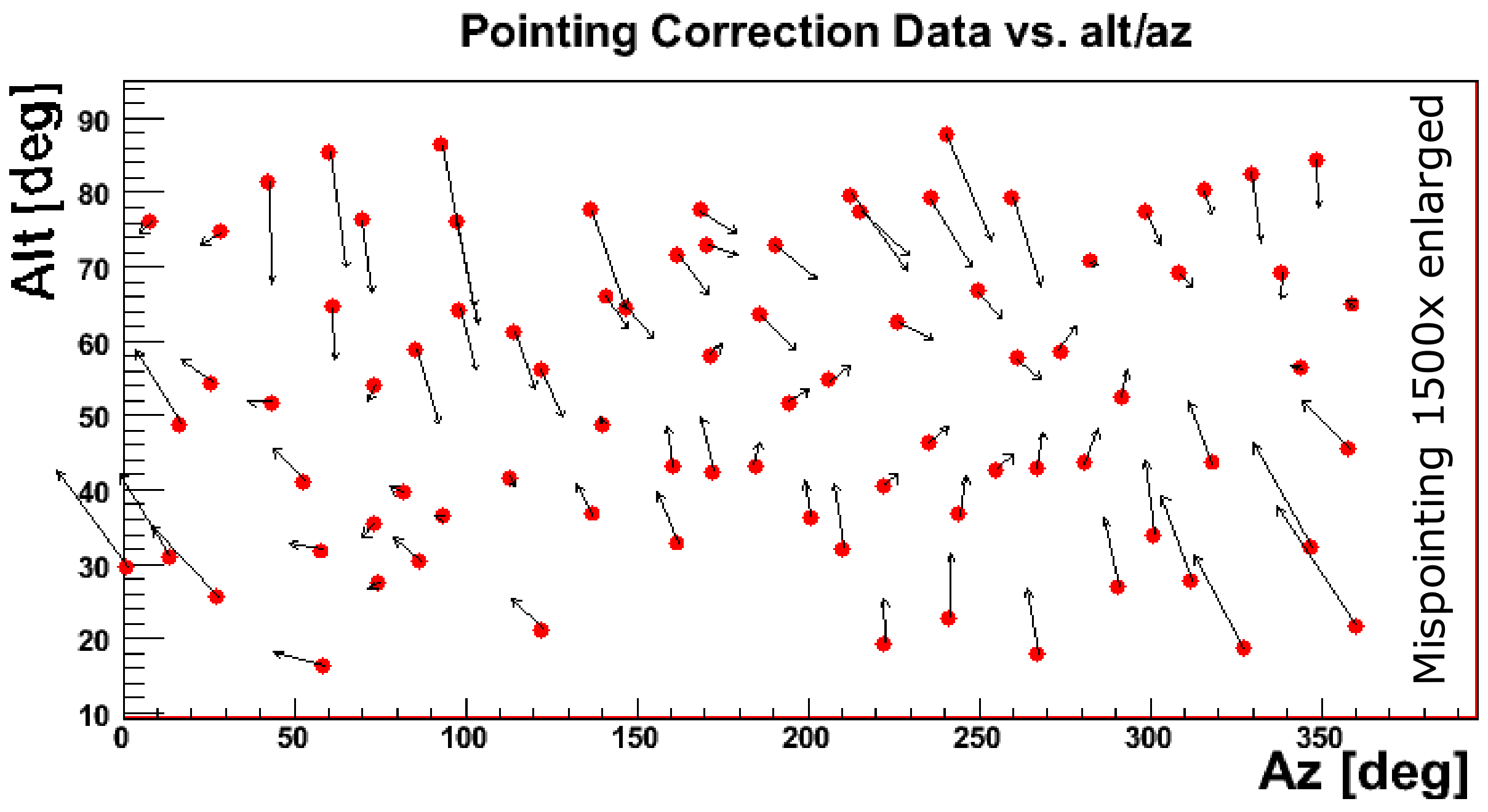
Thus the raw systematic error can exceed the statistical one. Therefore one needs pointing corrections in order to lower the pointing error.

The mispointing is measured by means of a CCD camera

As the point spread function is similar in size to the pixels of the PMT camera at the primary focus, the PMT camera can't be easily used to determine the precise pointing.

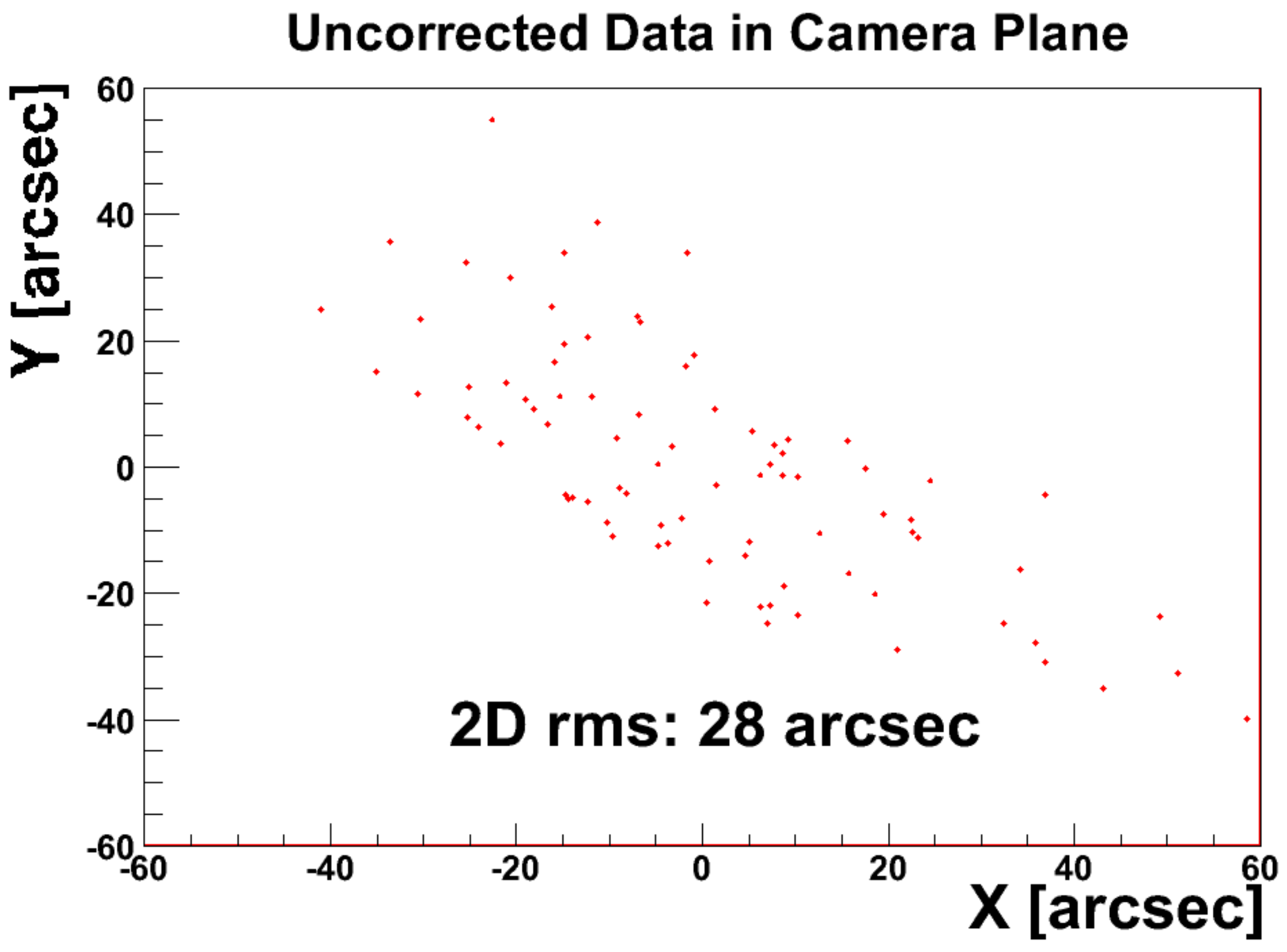

PSF of CT-3 in comparison with the size of a pixel (hexagon)

Instead a CCD camera is mounted in the middle of the dish of each telescope. It observes star images on the closed lid of the PMT camera and can be used to determine the pointing.



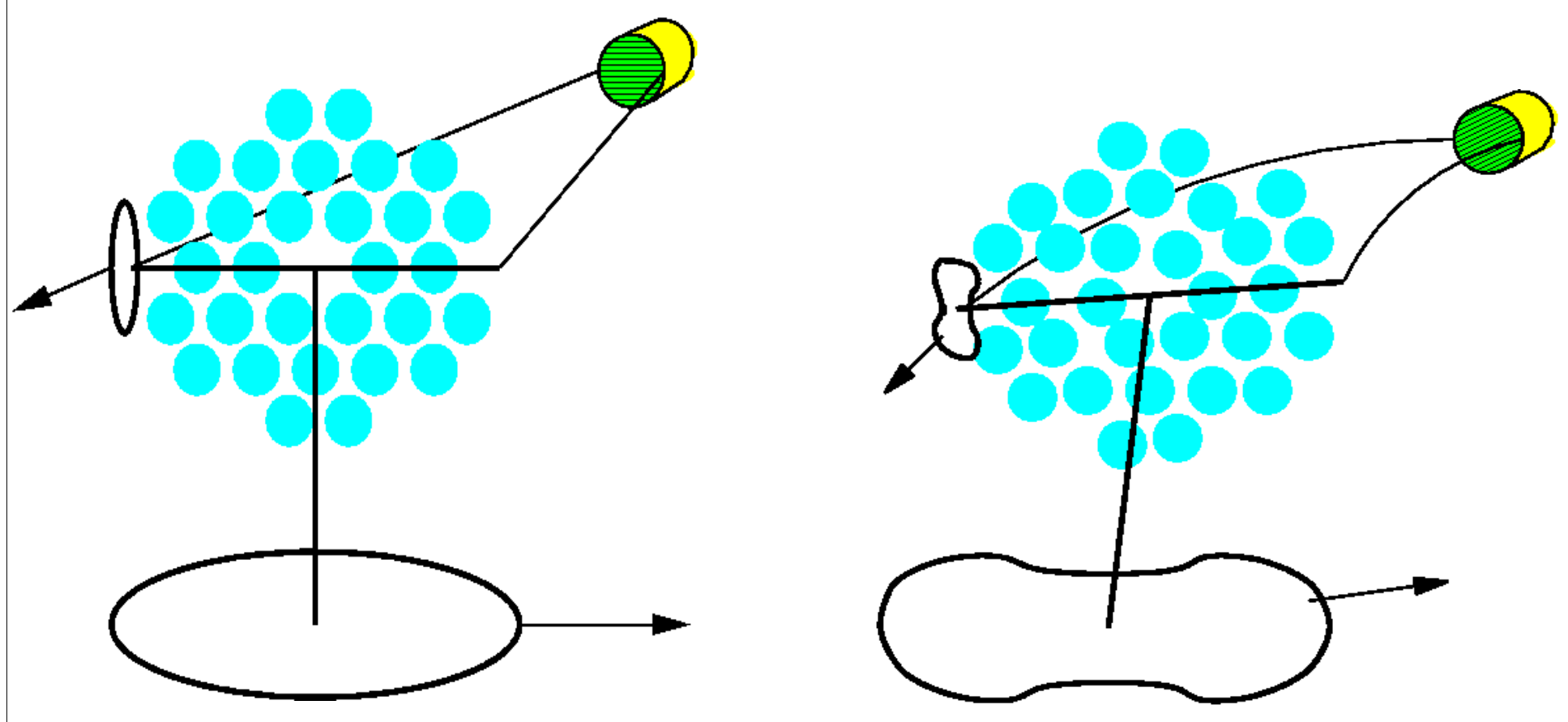
The mispointing is mainly a function of the telescope's attitude: azimuth and altitude

In special runs the telescope is pointed to a number of stars. For each star a CCD-image is taken. The position of the star image is related to the pixel matrix of the PMT camera using LEDs mounted on it. For each image the deviation from the nominal pointing is found. The result can be shown as a field of mispointing vectors at different telescope pointings (figure above, the mispointing is greatly exaggerated). In the figure below, the same data are used, showing how the images are distributed in the focal plane.



The mispointing is mechanically modelled

A 15 parameter model whose parameters can be interpreted mechanically is fit to the data. With the model one can predict the mispointing. Its parameters can also be used to monitor the mechanical stability of the telescope.



Telescope pointing
= nominal pointing

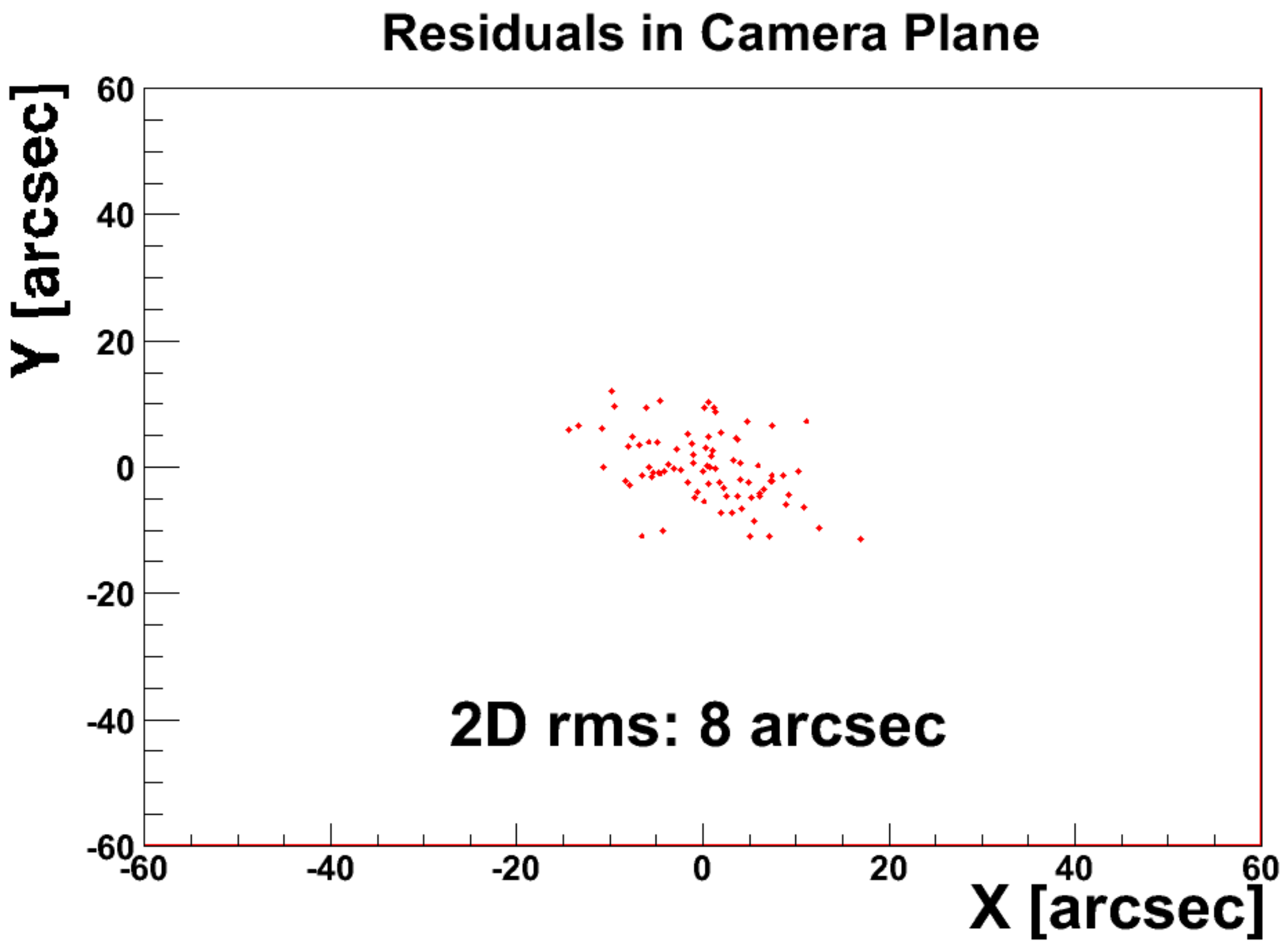
Telescope pointing
= nominal pointing
+ bending
+ first harmonic errors of shaft encoders
+ shaft encoder offsets
+ tilt of axes
+ camera offsets

By applying the fit model the pointing can be predicted with 8'' precision

The remaining residual is still higher than the desired precision. It is due to:

1. Reproducible mechanical effects not represented by the model, e.g. higher order periodic errors or drive rails' shapes (4.1'')
2. Irreproducible effects, such as wind load, obstacles on the drive rails or the positioning accuracy of the drive system (3.5'')
3. Fundamental limits, e.g. resolution of the CCD or accuracy of the LED positions (2.5'')

The measured value (8'') is in agreement with the quadratic sum of points 1 to 3 (5.9'').



Using observed positions of stars in a second CCD during data taking improves the precision further...

Each telescope is equipped with a second CCD camera mounted parallel to the optical axis. It observes star positions during normal Cherenkov data taking. The positions are compared with the ones predicted by the model. The measured deviations arise from points 1 and 2 from above. This fact is checked in dedicated off-runs by looking at the correlation of the deviations from the model in both CCDs. As they are highly correlated the second CCD actually measures the current mispointing. Offline it is applied as second order correction improving the precison

...to 2.5'' pointing resolution (2D rms)

as expected from the principle limits (point 3).