Micro-arcsecond Astrometry Technology: Detector and Field Distortion Calibration

Michael Shao[1], Chengxing Zhai[1], Bijan Nemati[2], Inseob Hahn[1], Russell Trahan[1], and Slava Turyshev[1]
[1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA
[2] Tellus1 Scientific, LLC, Madison, AL 35758, USA
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Speaker: Bao Yuxi

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1 Background

- Micro-arcsecond (μas) astrometry is an indispensable technique to detect earth-like exoplanets, fully characterize exoplanetary orbits, and measure their masses—information critical for assessing their habitability.
- Broader Applications:

Useful in dark matter research, and studying black holes, neutron stars, and microlensing effects to understand the early universe.

- Compared with the radial velocity (RV) method:

Astrometric detection is less affected by perturbations due to stellar activities and has better sensitivity for longer period exoplanet.

1 Background

- Going beyond Gaia to achieve narrow field micro-arcsecond (µas) astrometry enables to detect earth-like exoplanets by measuring the reflex motion of the host stars (Unwin et al. 2008).

- Gaia's end-of-mission accuracy : 10–20 µas (Lindegren 2020a, 2020b).
- The best Hubble Space Telescope (HST) accuracy : 20–40 µas (Riess et al. 2014).

- NASA's priority flagship mission for the next decade will be a 6 m telescope for observing habitable exoplanets and in the search for new physics.
- They mission concepts call for technologies to calibrate detectors and optical field distortions to achieve µas accuracy needed for reduction of the systematic errors due to imperfect detectors and optics down to sub-µas.

2 Calibration Architecture

➢System Architecture Overview

They're working with a 6-meter telescope equipped with a focal plane array detector, aiming for micro-arcsecond (μas) precision.

➢Detector Calibration

- Calibrating Pixel Geometry with Focal Plane Metrology:

  They shine laser patterns directly onto the detector to precisely map out each pixel's location.

  This method nails down pixel positions to an accuracy of 1e-4 pixels.

- Boosting Accuracy in Centroid Measurements:

  With each pixel's location pinpointed, they can calculate the center of stellar images much more accurately.

  This calibration technique drastically reduces measurement errors to the micro-pixel level.

2 Calibration Architecture

➢Field Distortion Calibration

- Understanding and Modeling Field Distortions:

Field distortions, mainly caused by imperfections in the telescope's optics, can skew the measurements.

They tackle this by observing densely packed star fields and fitting the data to low-order polynomial models.

- Calibration Through Systematic Observations:

By methodically shifting their observations across the star field, they collect ample data to construct and refine they distortion models.

This process significantly enhances the precision of their astronomical measurements.

3 Results

➢3.1 Pixel Geometry Calibration：

The leading order inter-pixel response variations are pixel QE (flat field response) and effective pixel locations in the array, which can deviate from a regular grid.

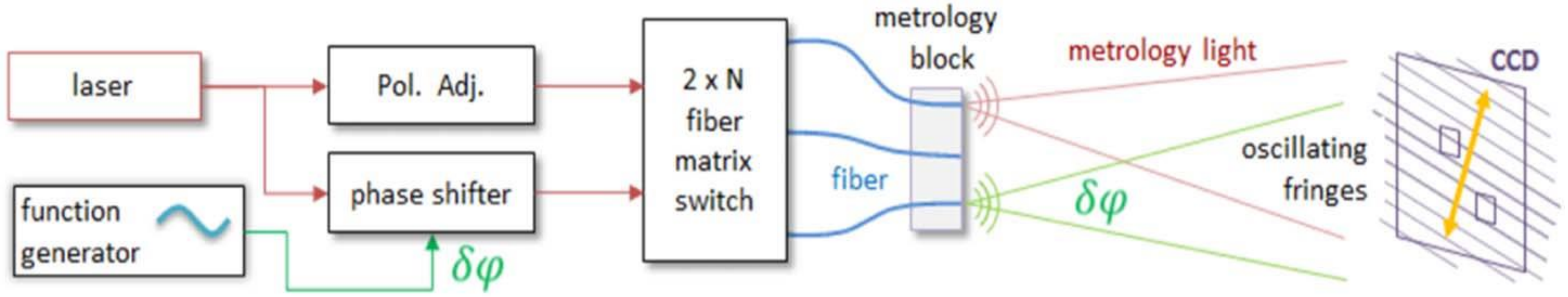

Figure 1. High-precision calibration of focal-plane errors uses moving fringes placed on the detector. Each pixel's location can be derived from the measured phase and amplitude of the fringe at that pixel.

3.1 Pixel Geometry Calibration

- They have characterized an E2V CCD39 with an array size of 80 × 80 for flat-field response and x- and y- direction pixel-location irregularity.

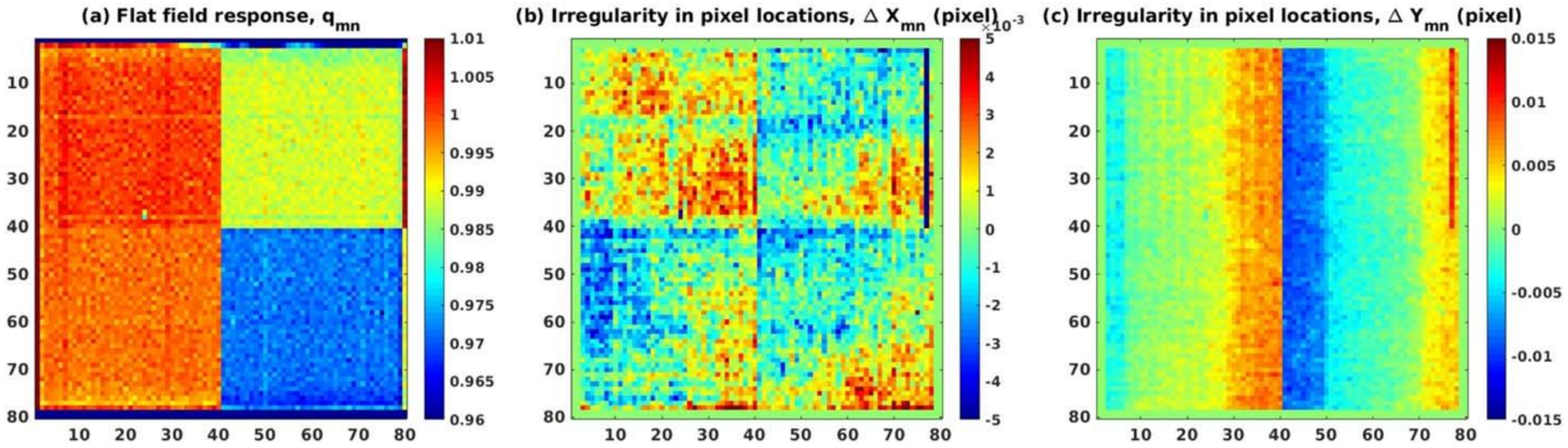

Figure 2： Left: Flat-field response;
Center: Pixel-location irregularity (row, X);
Right: pixel location irregularity (column, Y).

Accuracy of Differential Centroiding of Pseudo-stars

- The brightness centroid is an effective measure of the position of a stellar image.
- Inter-pixel response variations directly affect centroiding stars in the field.
- The ultimate test of the accuracy of focal-plane calibration and centroiding is an astrometric validation experiment.

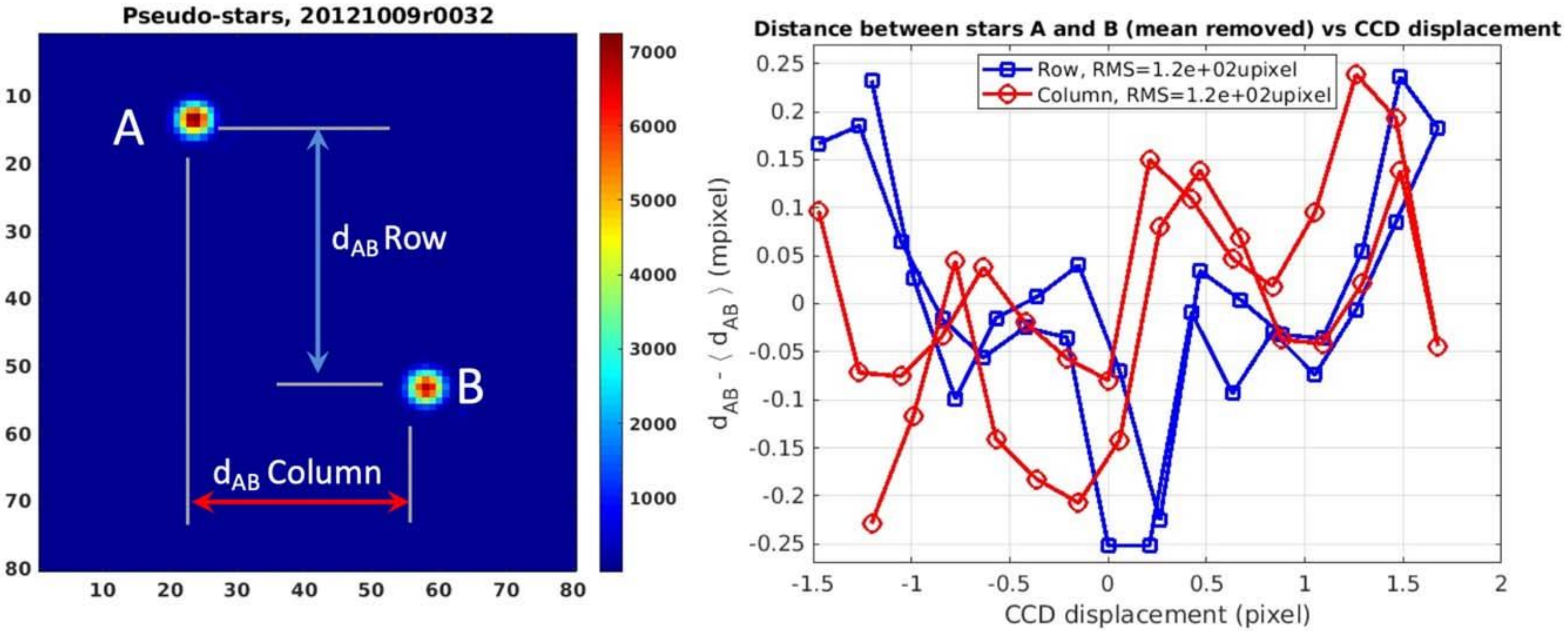

Figure 3. (Left) An astrometric test measures the consistency of inter-star distances on the focal plane as the line of sight is changed. (Right) Results of an astrometric test: centroid distance between pseudo-stars A and B in row and column directions, with mean removed, vs. the displacement of the CCD.

3. 2 Field Distortion Calibration

- Field distortion in a telescope means that stars imaged by the telescope do not appear in the locations corresponding to the angular positions of the stars with perfect fidelity as a geometric projection from the plane of sky.
- They conducted simulations tracing millions of rays at ~10,000 points in the FOV and found that the radial distortion can be modeled to very high accuracy, < 1μas.

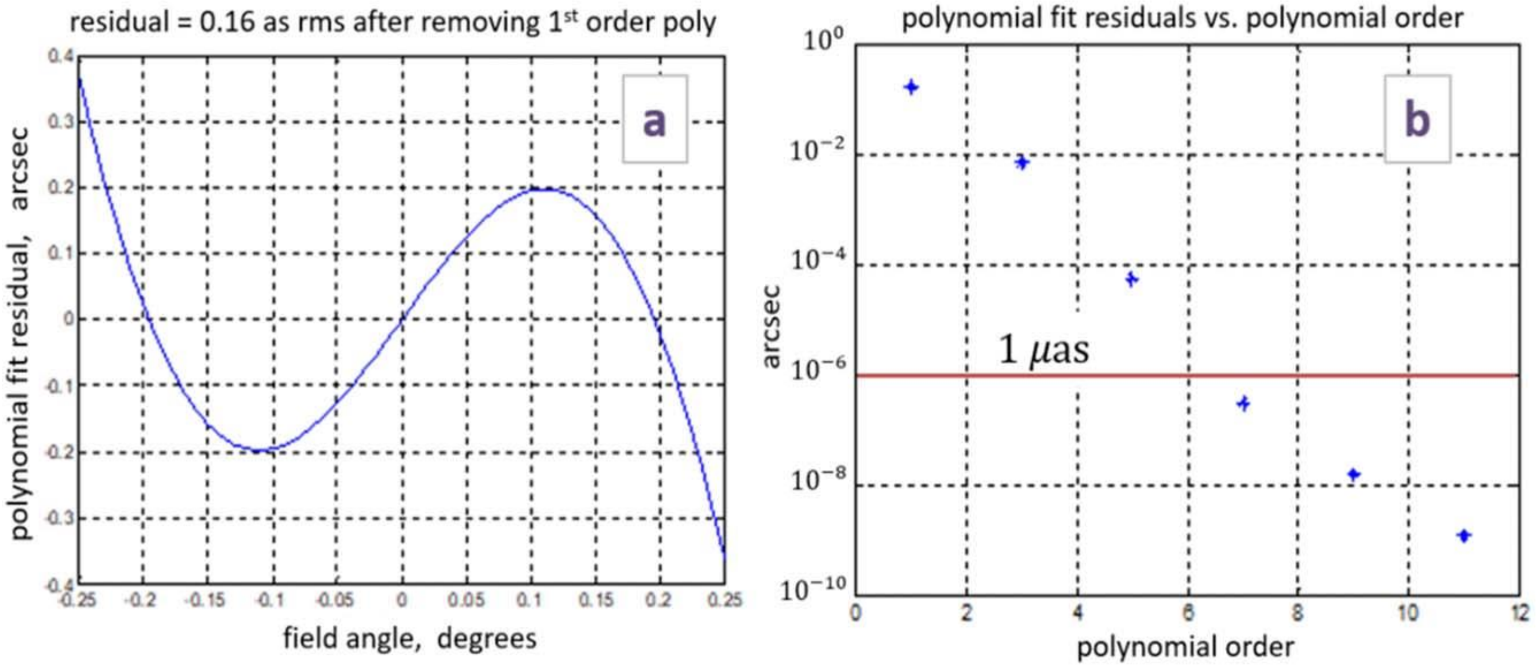

Figure 4. Modelling optical distortion and its removal.

(a) the residual radial field distortion after removing a linear radial trend;

(b) the rms error, in arcseconds, after removing a polynomial fit of successively higher orders. The line at 1 μ as represents a reference point and also the approximate allocation to this error.

3.2.1. Field Distortion from Optics Fabrication Errors

In this section, they evaluate the astrometric distortions caused by a tertiary mirror that has a λ/20 p–v wave front error, where the p–p (peak-to-peak) beam walk is 50% of the diameter beam (see Figure 5).

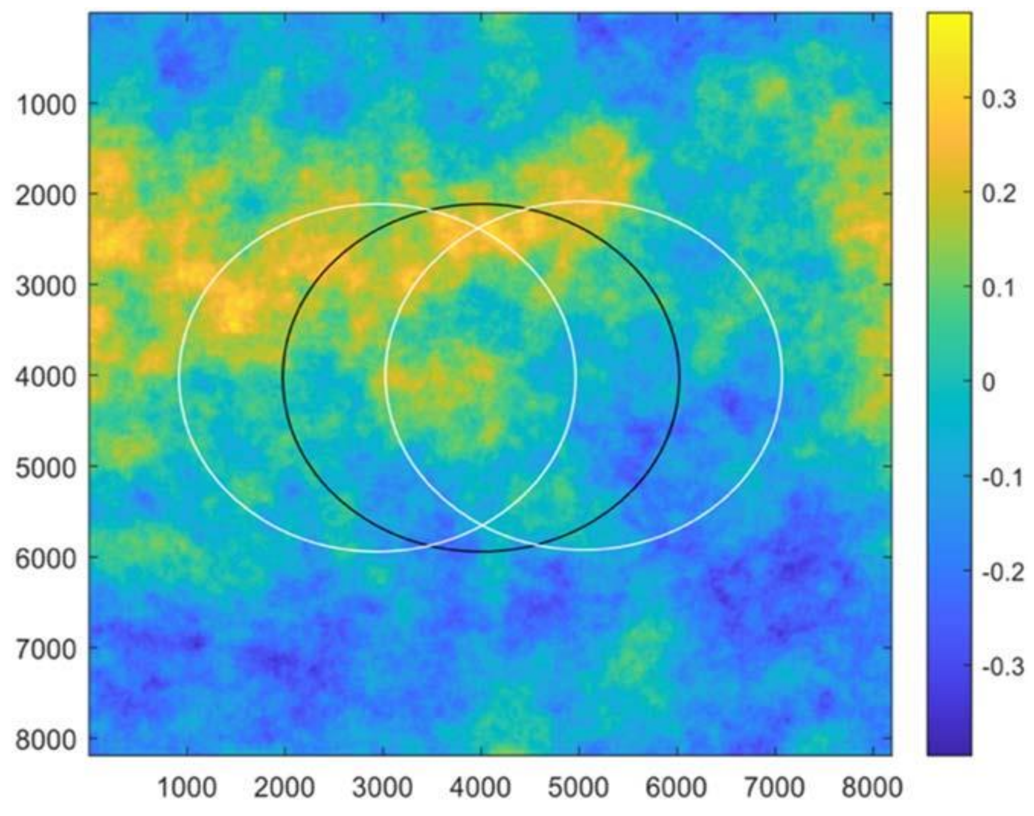

Figure 5. Generated phase errors (rad) as an 8K x 8K array representing the optical surface of the tertiary mirror, where the two circles of diameters of 4K points represents two optical footprints on the mirror surface at the opposite sides of the FOV.

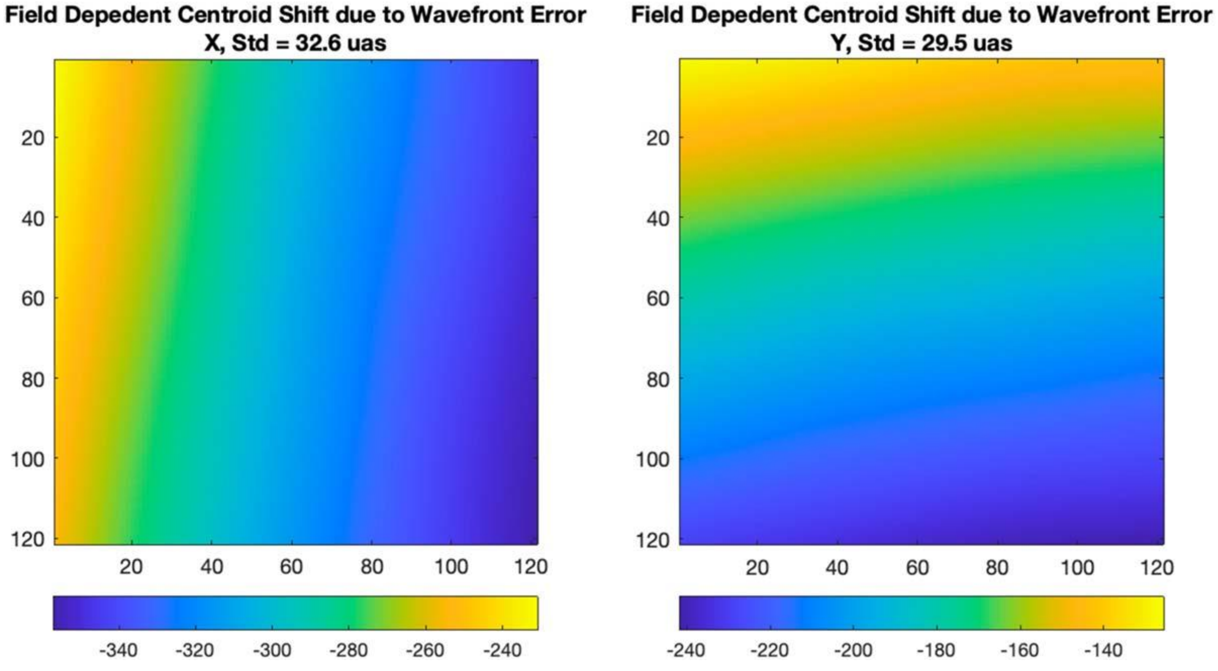

Figure 6. Field-dependent centroiding error due to beam walk on the tertiary optics with wave front error of λ/15 (p–v).

3.2.1 Field Distortion from Optics Fabrication Errors

The centroid shift is a slowly varying distortion function over the field with a p–v range of 100 μas.

It can be modeled by a two-dimensional polynomial model and calibrated by using reference stars in the FOV.

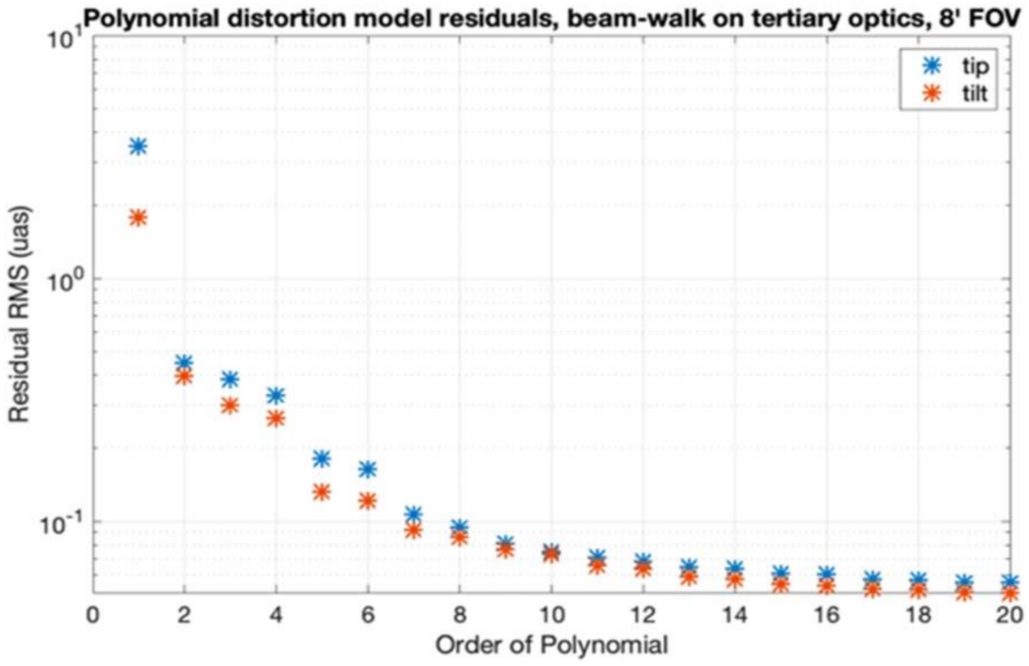

Figure 7. RMS of field distortion residuals as function of the order of the polynomial model.

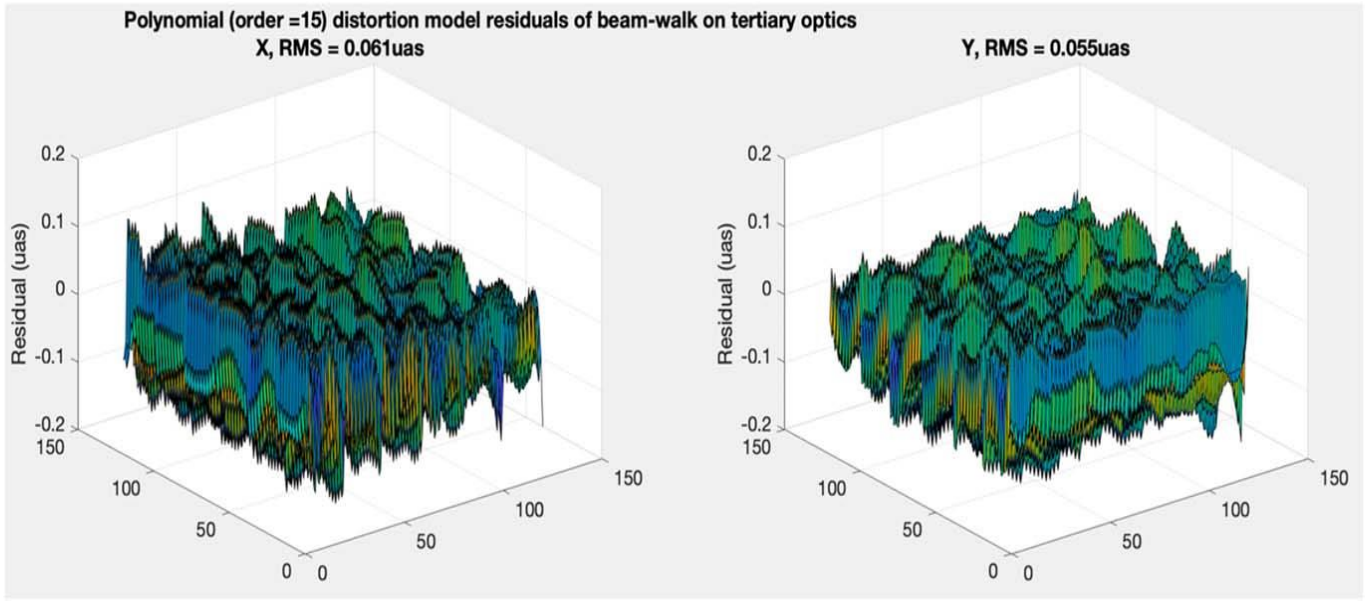

Figure 8. Distortion Residuals over the field using a 15th order polynomial model.

3.3 Centroiding using Diffraction Spikes

- In astrometric detection of exoplanets, quite often, the target star is very bright (~ 0–8 mag) while the reference stars are dim (~ 12–19 mag).
- For the brightest nearby stars, the image will saturate the detector.
- In this section, they describe a simulation study to answer how we can accurately centroid a saturated star using the diffraction spikes. The parameters used for simulation are displayed in Table 2.

Table 2
Parameters used for Simulation Study to Perform Astrometry using Diffraction Spikes

Telescope Diameter (m)	6
Secondary (m)	1.8
Width of spider (m)	0.12

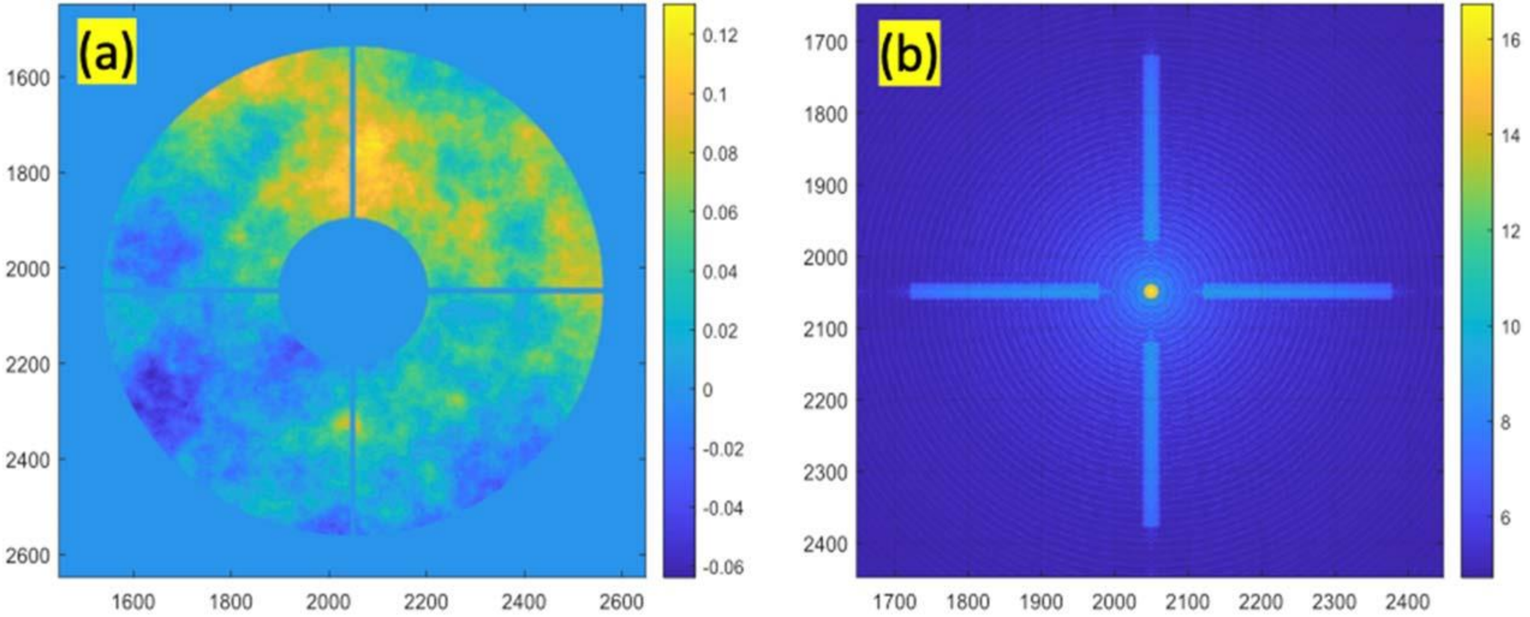

Figure 9. (a) Wave front errors (radian) over the pupil with an amplitude of λ/100 in rms or λ/18 peak-to valley;
(b) point-spread-function in log scale and mask used for centroiding spikes.

3.3.1 Calibration of Core-spike Astrometric Bias

- They shall call the offset between the PSF core centroid and the diffraction spike centroid core-spike offset.
- Calibration of core-spike astrometric bias can be done by using an appropriately short exposures, such that the PSF peak of the bright star is below saturation for simultaneously centroiding the core PSF and the diffraction spikes to estimate the core-spike offset.

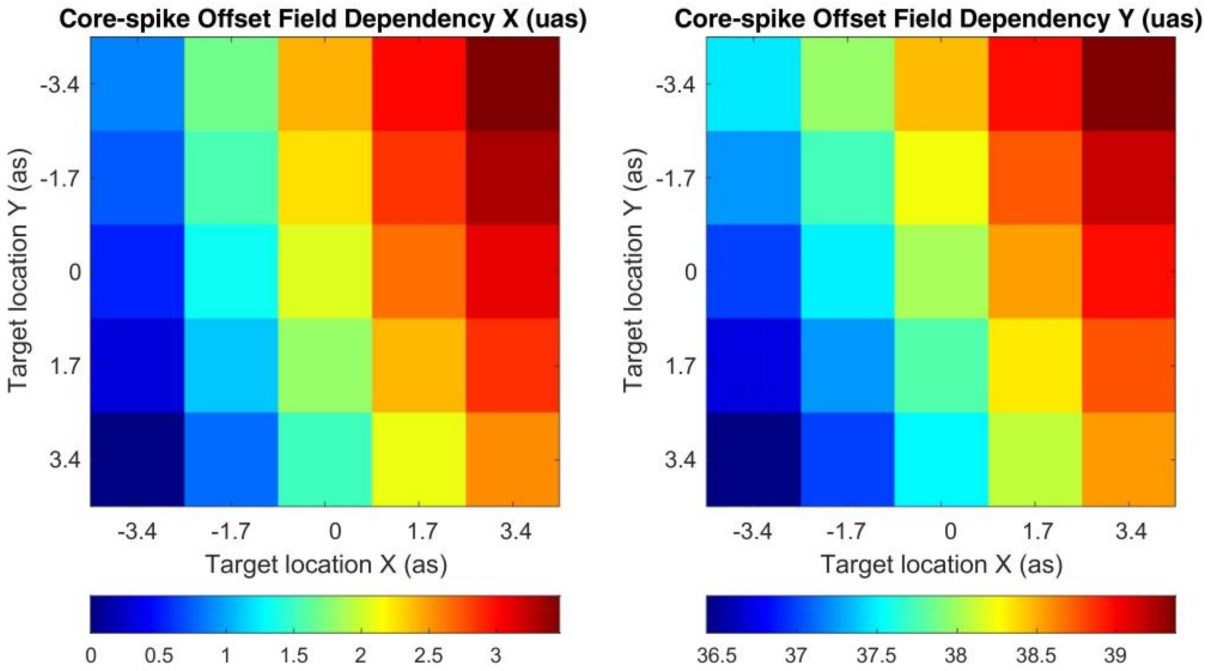

Figure 10. Core-spike offset as function of target location in the field of view.

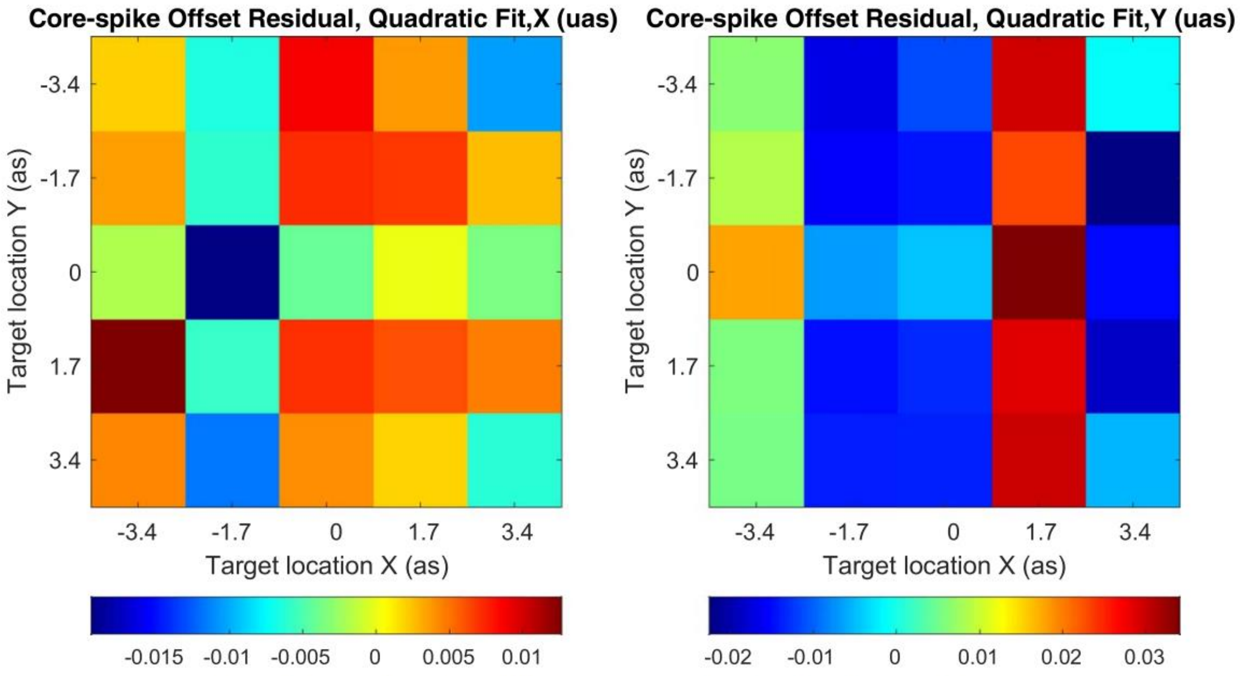

Figure 11. Core-spike offset residuals after fitting a quadratic function of target field position.

4 Summary

- In this paper, they have outlined an approach for μas-level narrow-angle relative astrometry and presented three technologies to calibrate errors due to detector, optics, and star saturation.
- The detector errors due to pixel geometry and QE gradients within a pixel can be calibrated with laser metrology.
- Optical errors lead to field distortion errors that can be modeled as low-order 2D polynomials and calibrated by observing dense star fields with dithers.
- Star saturation errors can be described by the “core-spike” offset, the astrometric offset between the centroid of a star’s core and the centroid of the diffraction spikes, which can be calibrated using high frame rate images.

Thanks!