Progress Towards μPixel Centroiding and μarcsec Astrometry

SPIE Astronomical Telescopes and Instrumentation

July 2012

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Outline, μas Narrow Angle Astrometry

- Major noise/error sources in micro-arcsec astrometry
  - **Photon noise**. The target objects are bright, photon limit is usually from the reference stars
  - **Beam walk** (optical errors). The stellar footprint on secondary, tertiary is different for different stars in the FOV. (more on this later)
  - **Focal plane** array
- Calibration of focal plane array errors
- Calibration of optical errors

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Photon Noise

Astrometric Error (uas) from photon noise (ref stars)

Telescope dia (m)

		0.35	0.50	0.70	1.00	1.40	2.00
	0.35	8.16	4.00	2.04	1.00	0.51	0.25
fov deg	0.50	5.71	2.80	1.43	0.70	0.36	0.18
	0.70	4.08	2.00	1.02	0.50	0.26	0.13

Photon noise from ~15 brightest reference stars in the field of view averaged over the whole sky. (slighty better in the galactic equator, worse at the poles)

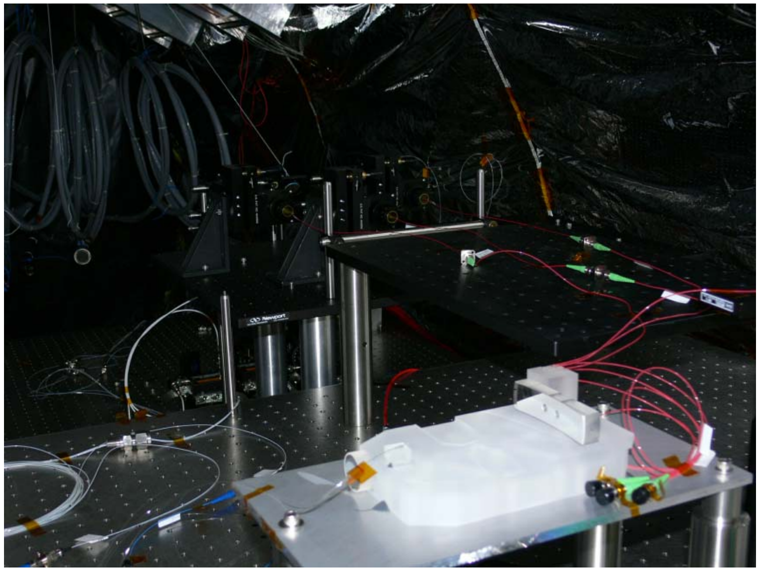
Accuracy increases linearly with FOV, and as the square of the telescope diameter. It goes as diameter squared because the # photons increases with dia^2 and the diffraction limited image is narrower with large telescope diameter.

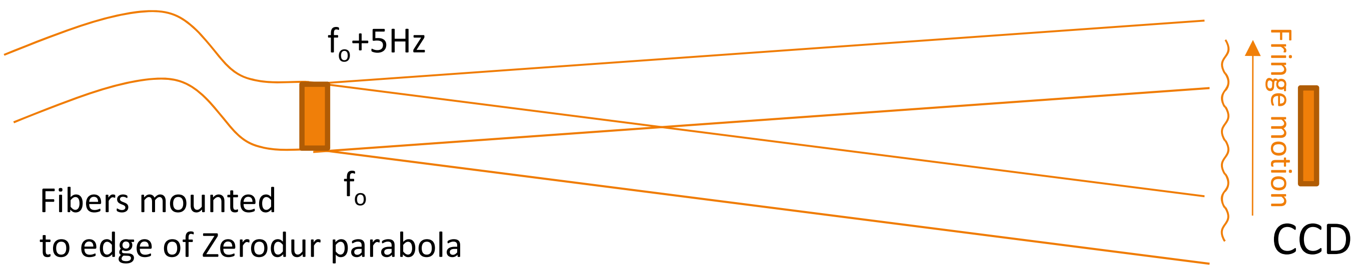
Calibrating CCD Centroiding Errors

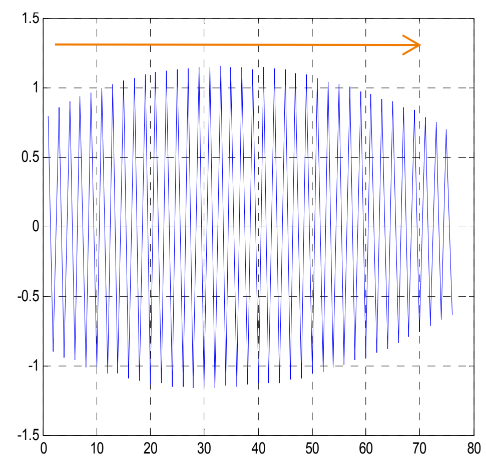
- Two/three classes of errors
  - Pixels are not uniformly spaced, (especially in mosiacs)
  - QE within a pixel is not uniform
  - Error in the assumed PSF
- Measuring Pixel positions at the upixel level
- Measuring QE variations within a pixel
- Nyquist sampling and measuring the PSF.
- Multi-color calibration

Micropixel Centroid Testbed I Pixel Position

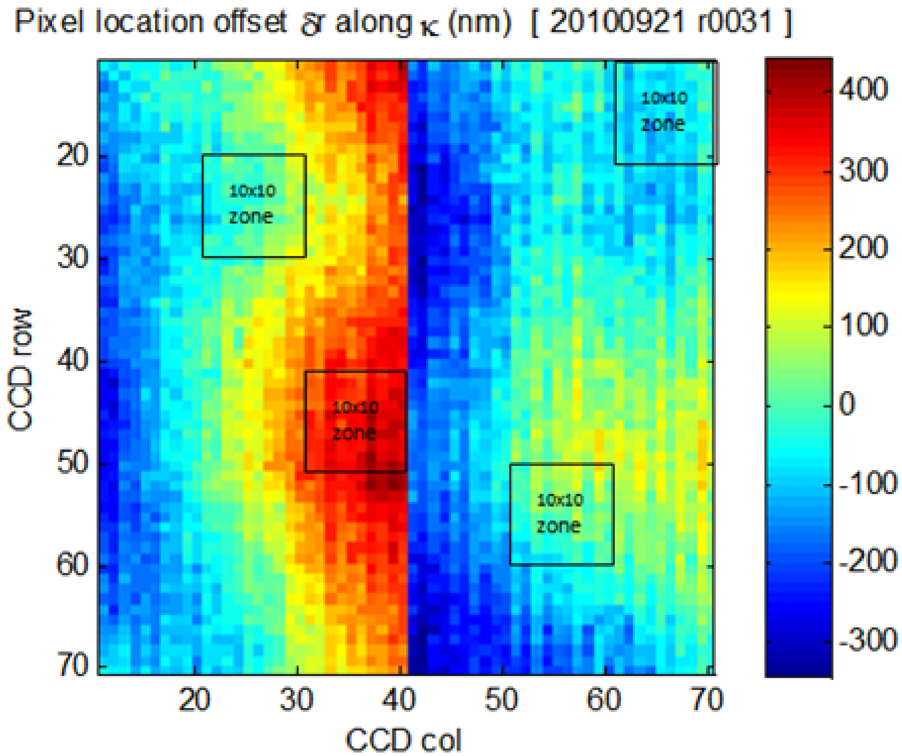
- 10^{-5} pixel centroid measurements are needed for 1uas astrometry with a 1m telescope. Current state of the art is about ~$2x10^{-3}$ pixel.
- The graph shows the spatial fringes across 80pixels of an E2V 39 CCD.
- The fringes move (left to right) at ~5hz, images are recorded at 50hz.
  - If the fringe motion is uniform, then one pixel's output is C0+C1*sin(w*t + phi(I,j))
  - Phi(i,j) gives us the location of the pixel

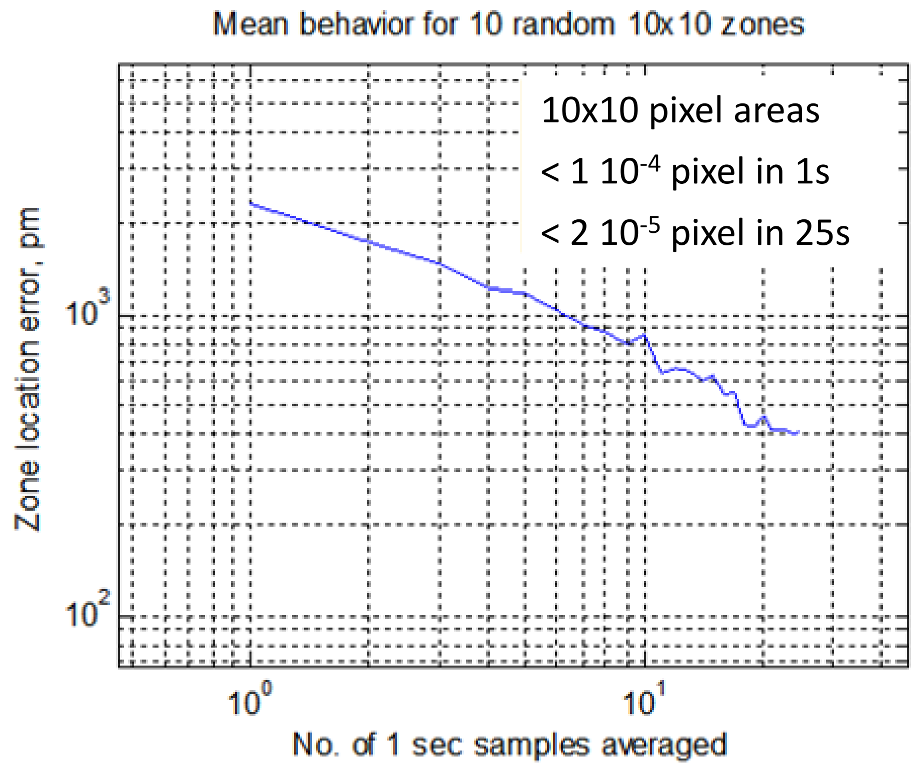






Testbed Results: Measuring Pixel Location

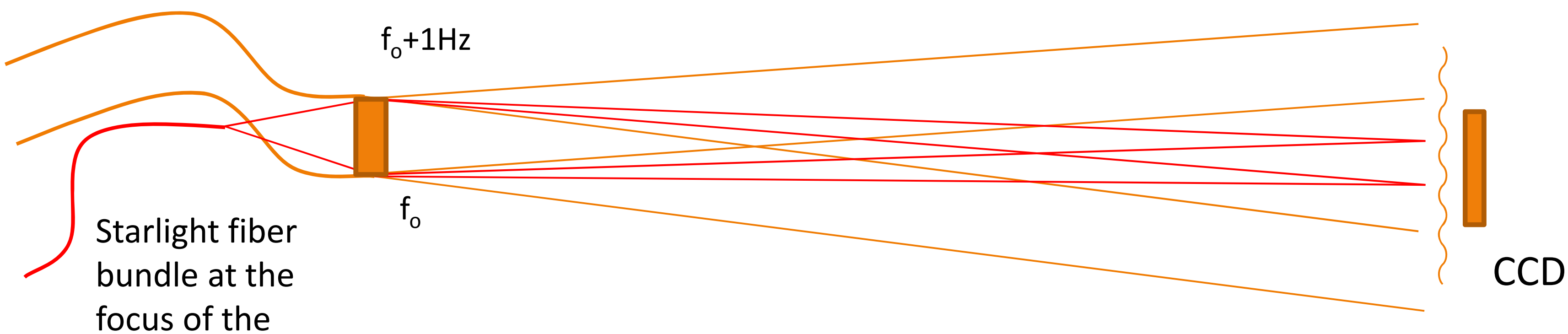




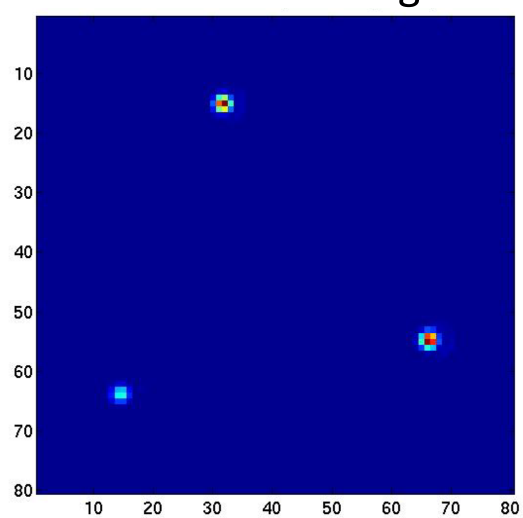
- If we were to fit a static fringe pattern across many pixels, the QE variations that are unknown would bias the pixel position.
- Instead, with heterodyne fringes, we measure the position of a pixel by looking at that pixel's flux versus time (phase of a sine wave in time).
- **We have demonstrated 2 10^{-5} pixel position measurement error for groups of 10x10 pixels in less than 25 seconds of integration.**

Testbed: Next Step

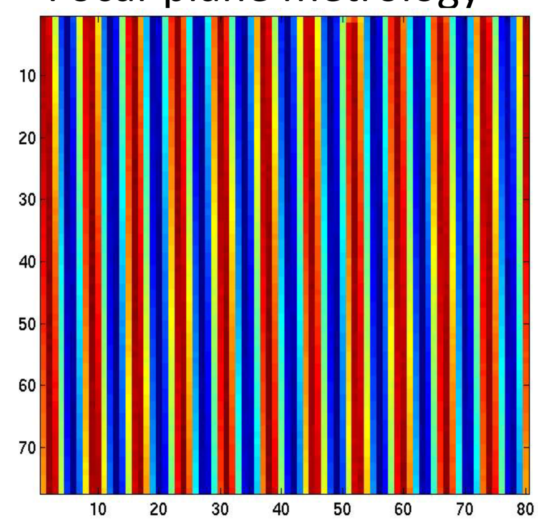
- Conduct 2D (X,Y) measurements of pixel position.
- Put pseudo-star images on the CCD and demonstrate centroiding to 10^{-5} pixels.



Pseudo-star images



Focal-plane metrology



Star Centroiding to 10^{-5} pixel

<u>Point Spread Function (PSF) definitions:</u>

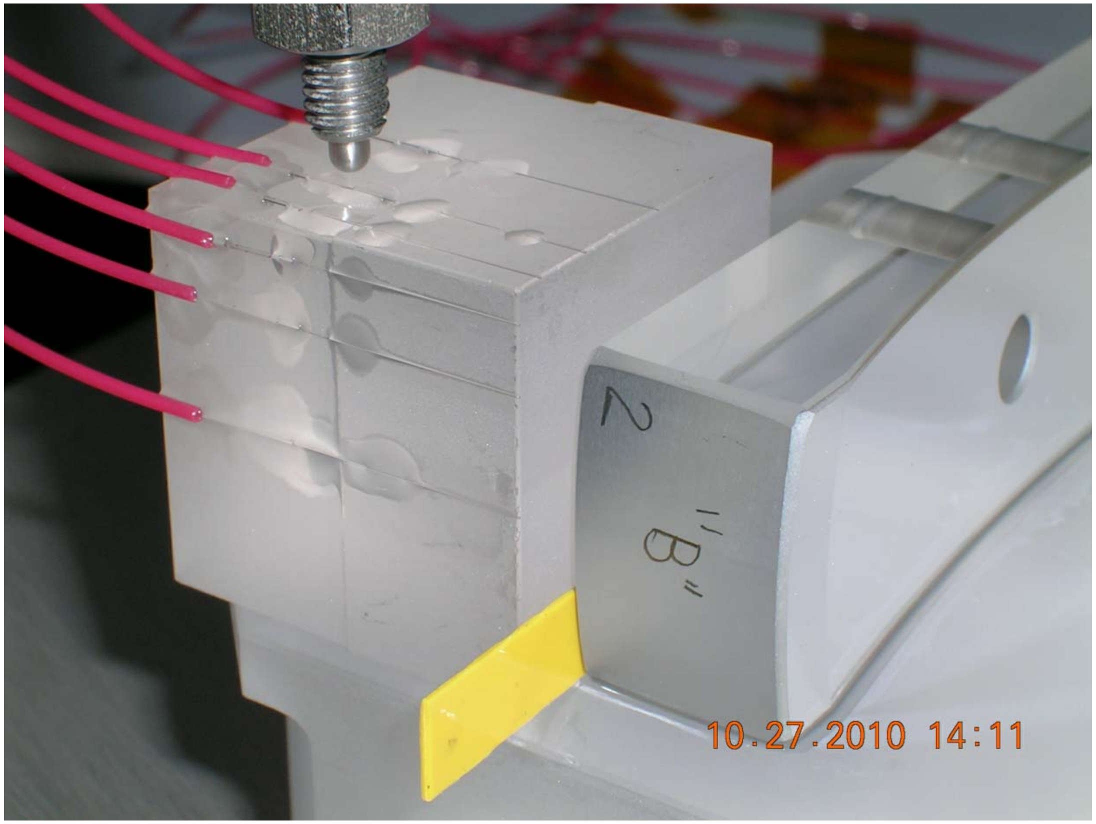
- **True PSF**: Image(x,y) at infinite spatial resolution.
- **Model PSF**: Our guess of what the true PSF is.
- **Pixelated PSF**: I(i,j), the integral of Image(x,y)·$QE_{i,j}$(x,y)·dx·dy

<u>Classical Approach for centroiding</u>:

- Perform Least-Square Fit of CCD data to the pixelated model PSF, fitting for x, y, intensity.
- Known problems:
  - True PSF differs from model PSF, true PSF changes with star color, position in FOV, and as the optics warp. But more important, the model PSF is not the true PSF.
  - Calculating the pixelated PSF from the model PSF requires knowledge of QE(x,y) within every pixel.
  - The canonical approach to measuring QE(x,y) is to scan a spot across each pixel. No done because of practical reasons: can't do all pixels at once, diffraction pattern spills over to next pixel, knowledge of the scanning spot position.

<u>NEAT Approach for centroiding:</u>

- **Nyquist** theorem: Critically sampling a band limited function at greater than 2*bandwidth is sufficient to **<u>perfectly</u>** reproduce that function.
  - We have the knowledge of the **<u>true</u>** PSF in the data, not a **guess** of the true PSF.
- We use laser metrology to measure QE(x,y) for all pixels simultaneously. In fact, we measure the Fourier Transform of QE(x,y), by putting fringes of various spacing and directions across the CCD.
- Numerical simulations show that QE(x,y) calibrated with **6 parameters** per pixel is sufficient for ~2×10^{-6} pixel centroiding for a backside CCD with P-V QE variation <10% across pixel.



- Measure pixel position and QE(x,y) within each pixel. By putting fringe patterns across the CCD with different fringe spacing and orientation. QE MTF is measures the fourier transform of QE(x,y) is measured.
- Numerical simulations show that QE(x,y) calibrated with **6 parameters** per pixel is sufficient for ~$2x10^{-6}$ pixel centroiding for a backside CCD with P-V QE variation <10% across pixel (assuming intra-pixel QE varies by <6%).

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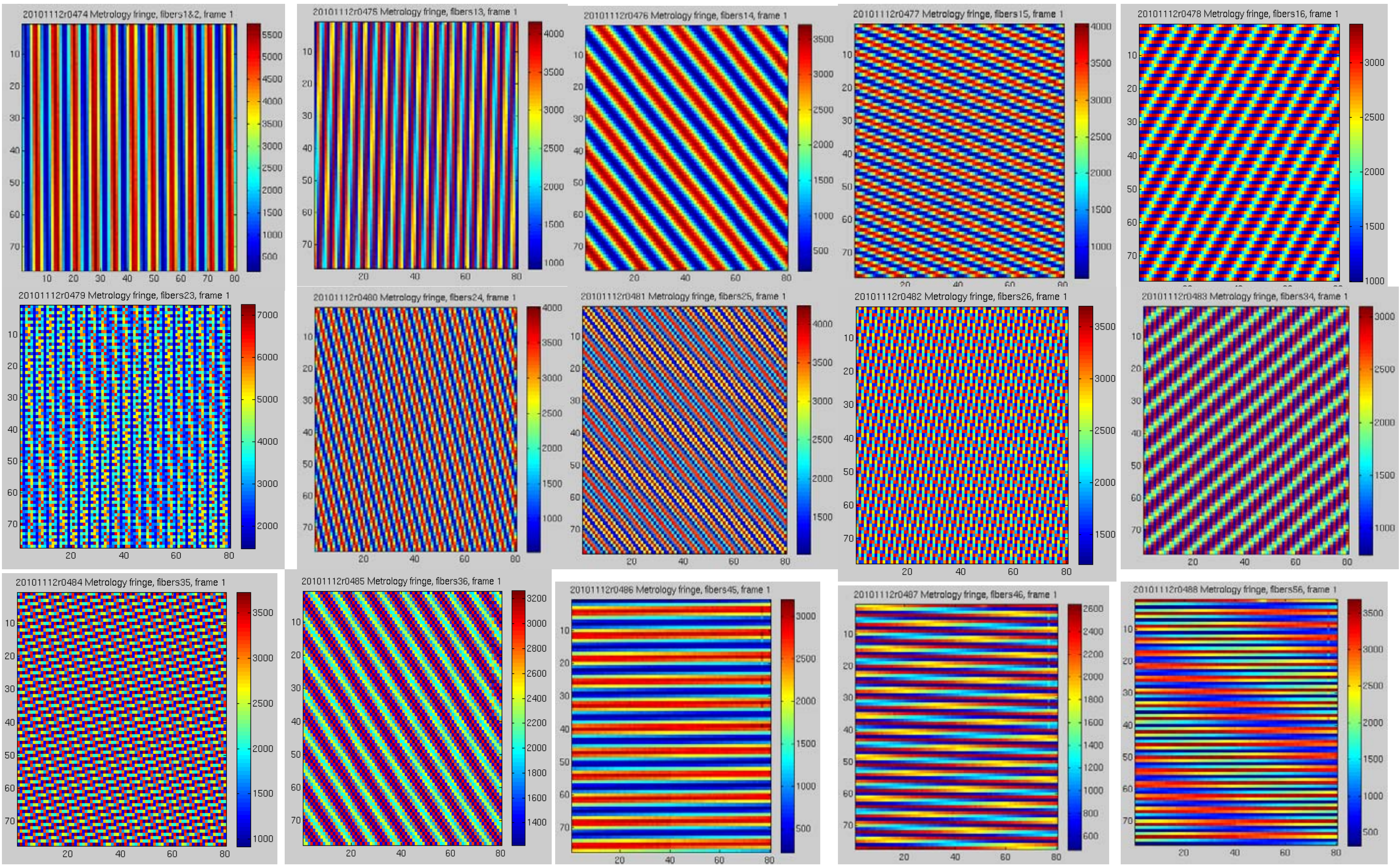
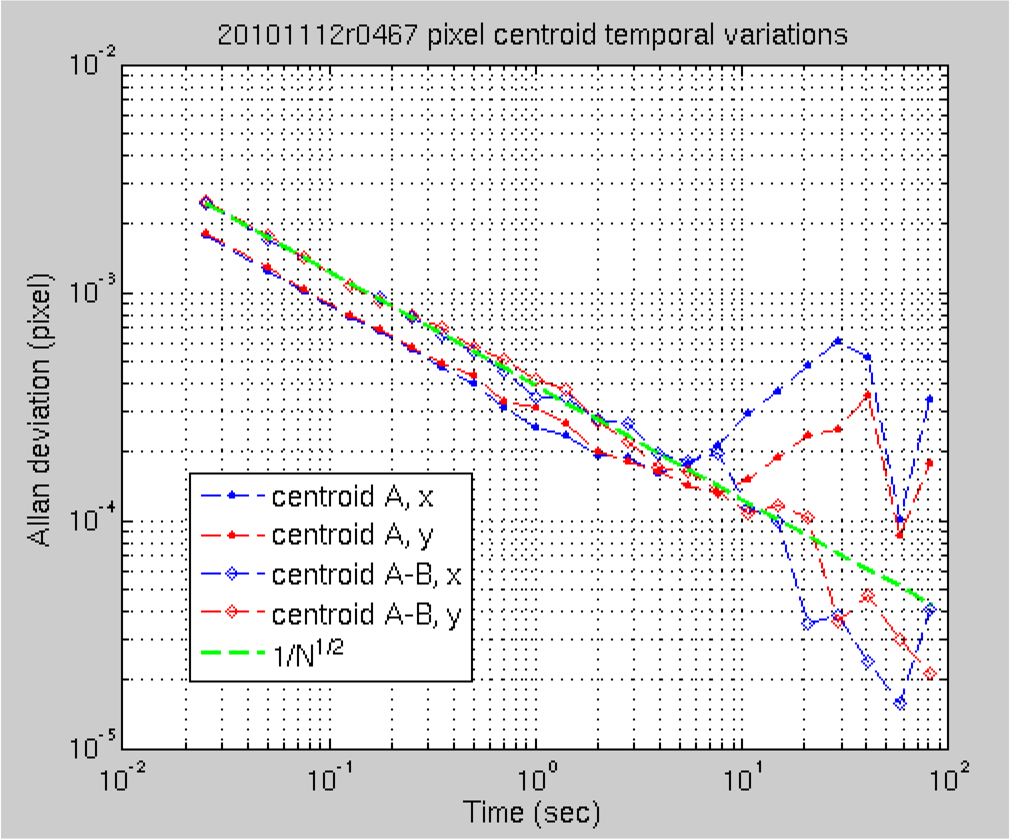
Sample Metrology Spatial Fringes



Centroid Allan Deviations



Single Fiber centroid reaches noise floor at 3e-4 pixels (drift)
Differential centroid continue to average down to ~4e-5 pixels after 100 sec integration

Yet to be done (coming year)

- To date, all of our calibrations and tests have been done at one wavelength (632nm). Stars are white light and the CCD pixel locations and the intra-pixel QE's may be wavelength dependent.
- Currently setting up to repeat all of the above at 4 wavelengths between 600nm and 800nm.

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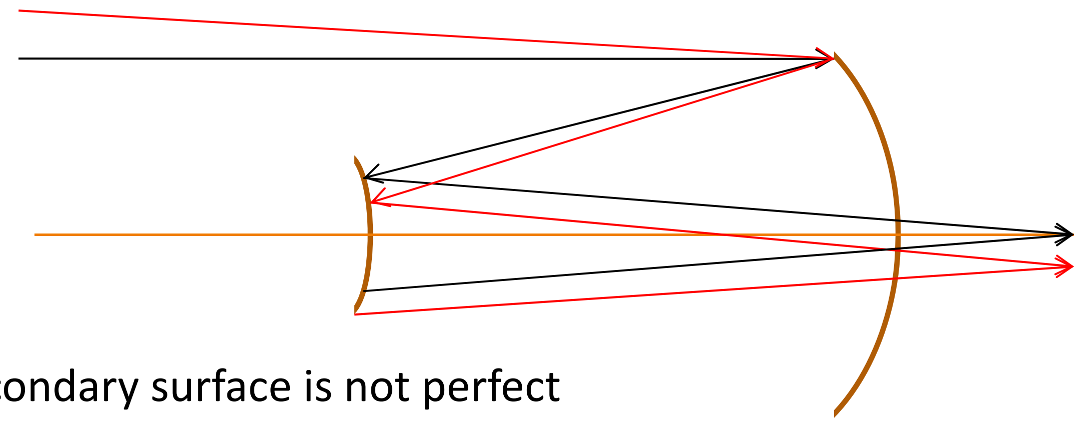
Optical Errors

- Beam walk errors



- If the secondary surface is not perfect
  at the 5pm level there will be systematic biases > 1uas.
- Biases that are constant (for multiple yrs) are OK. But 5pm stability is not
  possible for any optic over a period of years.

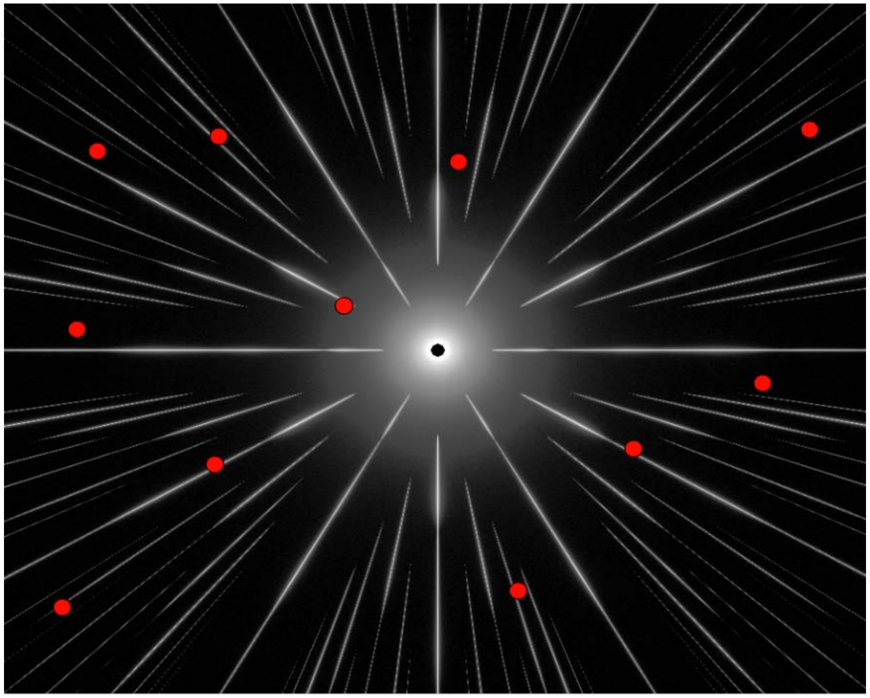
Detailed simulation results of **Beam walk error** in a 3 mirror TMA telescope (O. Guyon) would be **0.5~1 milliarcsec** if the secondary and tertiary optics are polished to **1nm** accuracy. Beam walk errors are smaller for smaller angles ~10uas for 10 arcsec field.

Calibration of Optical Distortion

- There are several approaches to calibrating optical distortion.
  - Continuous calibration (done during observation of stars)
    - Guyon (Diffractive mask)
  - Intermittent external calibration (using starlight)
  - Intermittent internal calibration (using laser light)

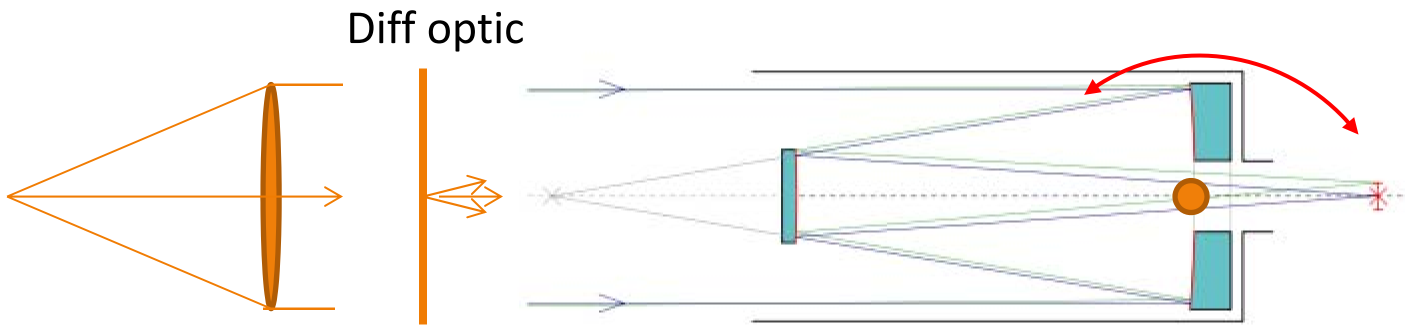
Diffractive Mask for Field Distortion Cal

- A diffractive mask is placed at the entrance pupil of the telescope. The mask in monochromatic light, produces a regular array of dots in the focal plane. A regular array of dots in the pupil becomes a regular array of dots in the image. In white light, the mask produces an array of radial spokes.

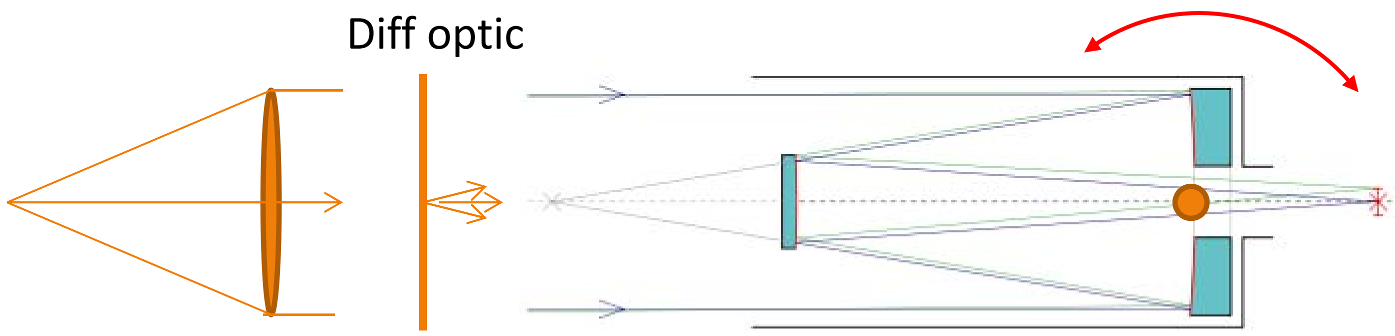


Lab Calibration of Field Distortion

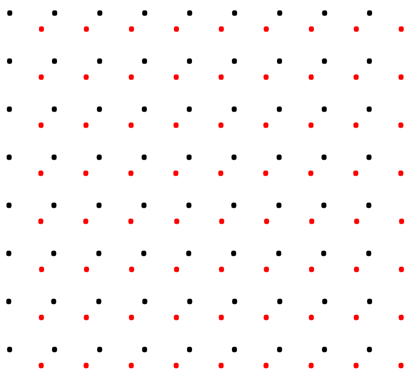
- Field distortion comes from
  - The optical design, (with perfect optics)
  - Imperfections in the optical figure (polishing error)
- Both errors are concentrated at low spatial freq. (Errors across 0.5 deg >> errors across 0.001 deg. Numerical simulations by Guyon showed errors ~ 10uas over a 20 arcsec field for state of the art optics.
- Diffractive grating generates spots every ~20 arcsec.



Lab Calibration of Field Distortion 2



- The diff optic produces a grid of dots in the focal plane
  - The deviation from a perfect grid as measured by the focal plane detector, is the field distortion
- The telescope is rotated (about the center of the primary) so that the wavefront errors from the collimator, and telescope primary doesn't change.
  - A few (2~3) of the dots in the grid can be used to measure the rotation of the telescope at the nano-radian level. From that we should be able to predict the position of all the other dots to ~10uas.



Summary

- We've started a series of lab experiments to demonstrate uas level narrow angle astrometry for two applications
  - Spacecraft navigation. (needs 1e-4 pixel accuracy) by measuring the position of 2 or more asteroids in the main belt against background stars in the GAIA catalog.
  - Astrophysics: narrow angle astrometry to find Earth sized planets around nearby stars, measure the masses of black holes with orbiting stellar companions etc.
- The first is calibration of the focal plane to enable 1e-5pixel centroiding.
- The 2nd is calibration of optics field distortion at the sub-nanoradian level, using diffractive optics.