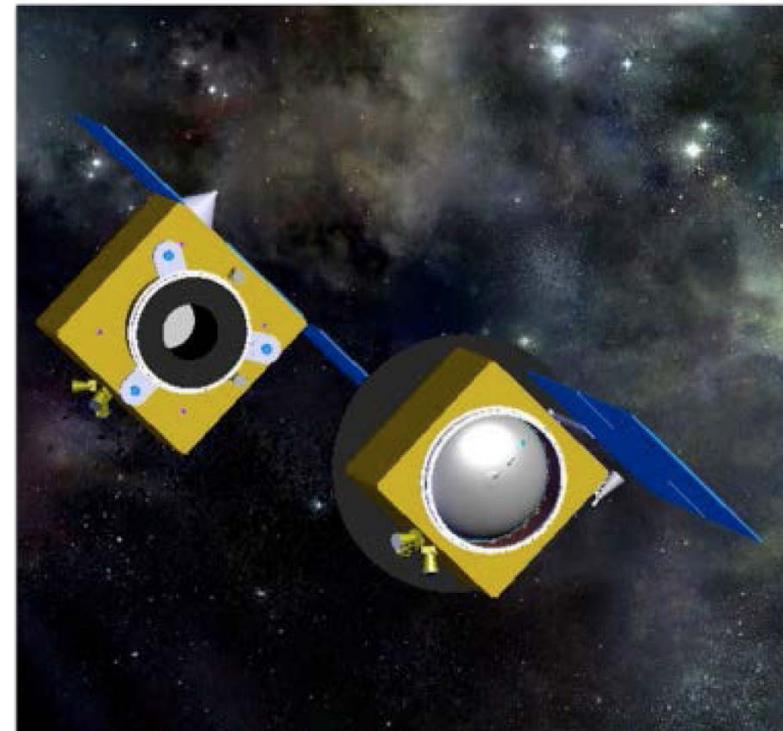
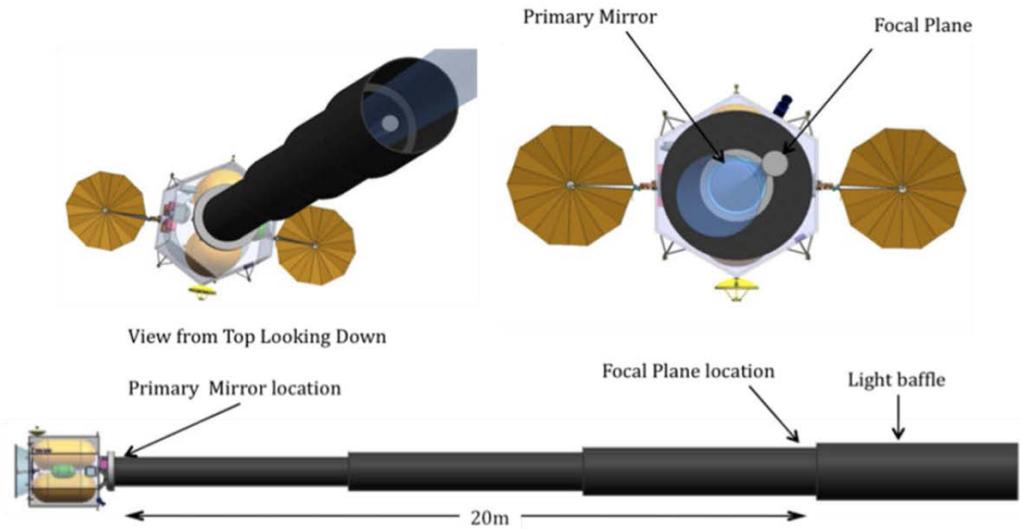




MicroArcsec Astrometry with Moderate Telescopes

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Outline, μ as 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



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
fov deg	0.35	8.16	4.00	2.04	1.00	0.51	0.25
	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 ~10 brightest reference stars in the field of view averaged over the whole sky. (slightly 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.



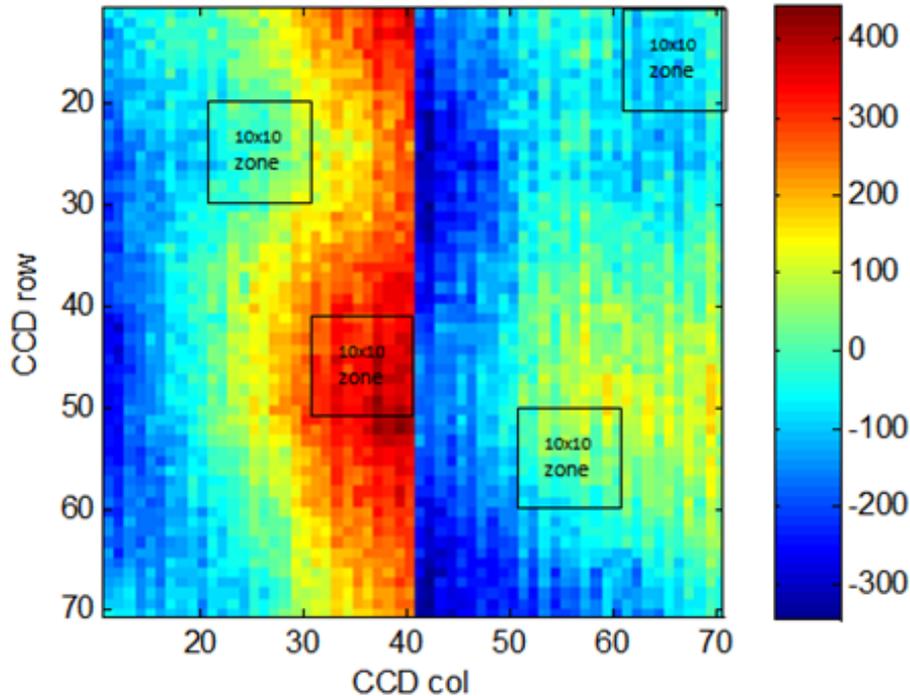
Calibrating CCD Centroiding Errors

- Two/three classes of errors
 - Pixels are not uniformly spaced, (especially in mosaics)
 - 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

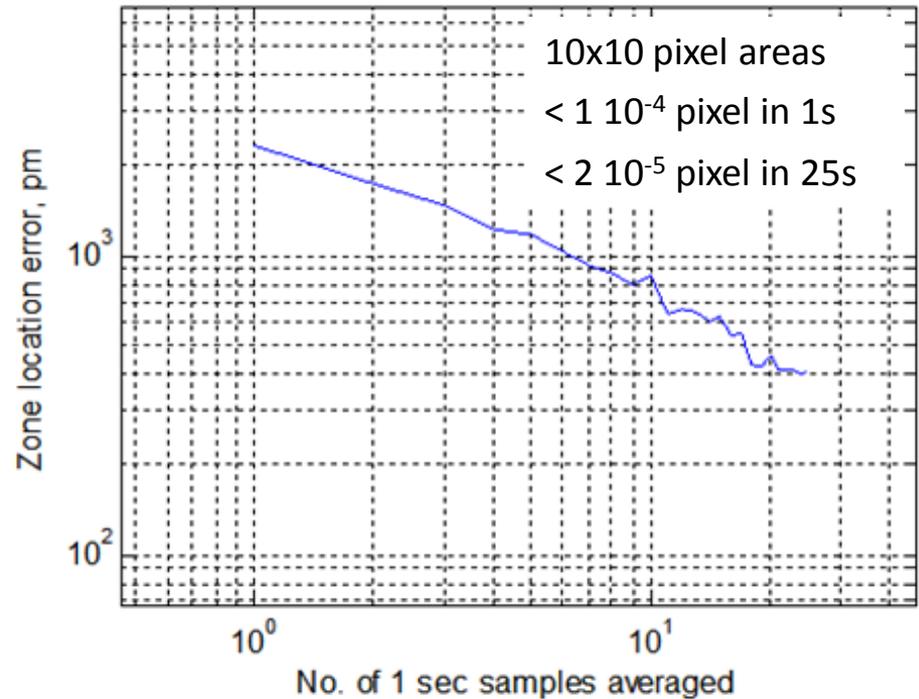


Testbed Results: Measuring Pixel Location

Pixel location offset δ along κ (nm) [20100921 r0031]



Mean behavior for 10 random 10x10 zones



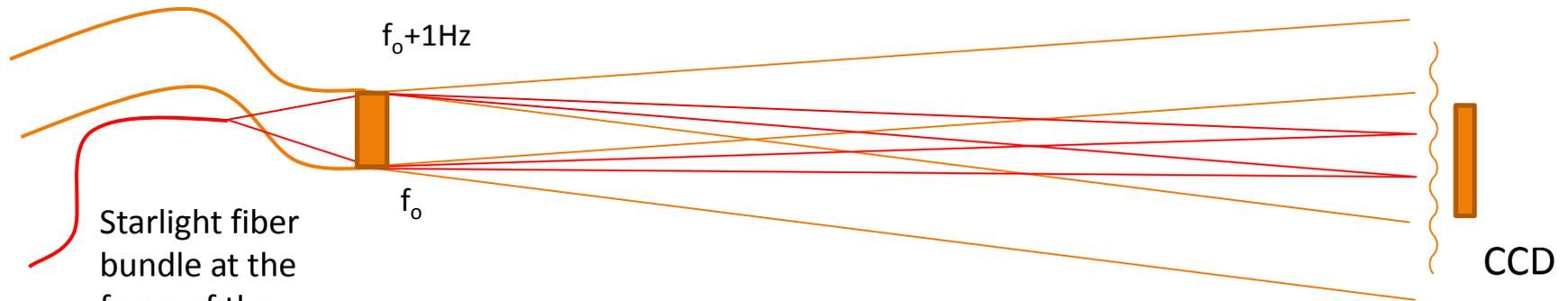
- If we were to fit a static fringe pattern across many pixels, the QE variations that are unknown would bias the pixel position.
- Instead, with heterodyne fringes, we measure the position of a pixel by looking at that pixel's flux versus time (phase of a sine wave in time).
- **We have demonstrated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



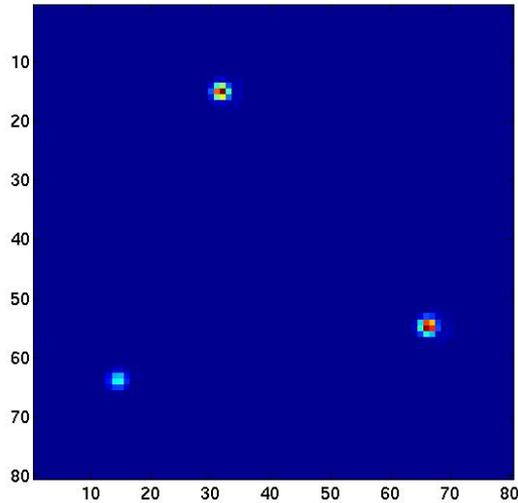
Testbed: Next Step

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

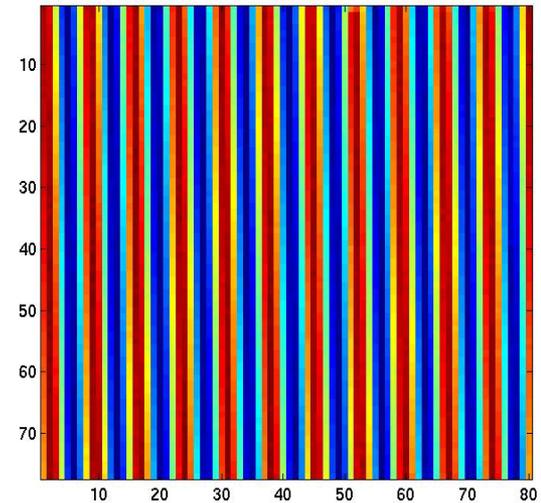
Metrology fibers



Pseudo-star images



Focal-plane metrology





Star Centroiding to 10^{-5} pixel

Point Spread Function (PSF) definitions:

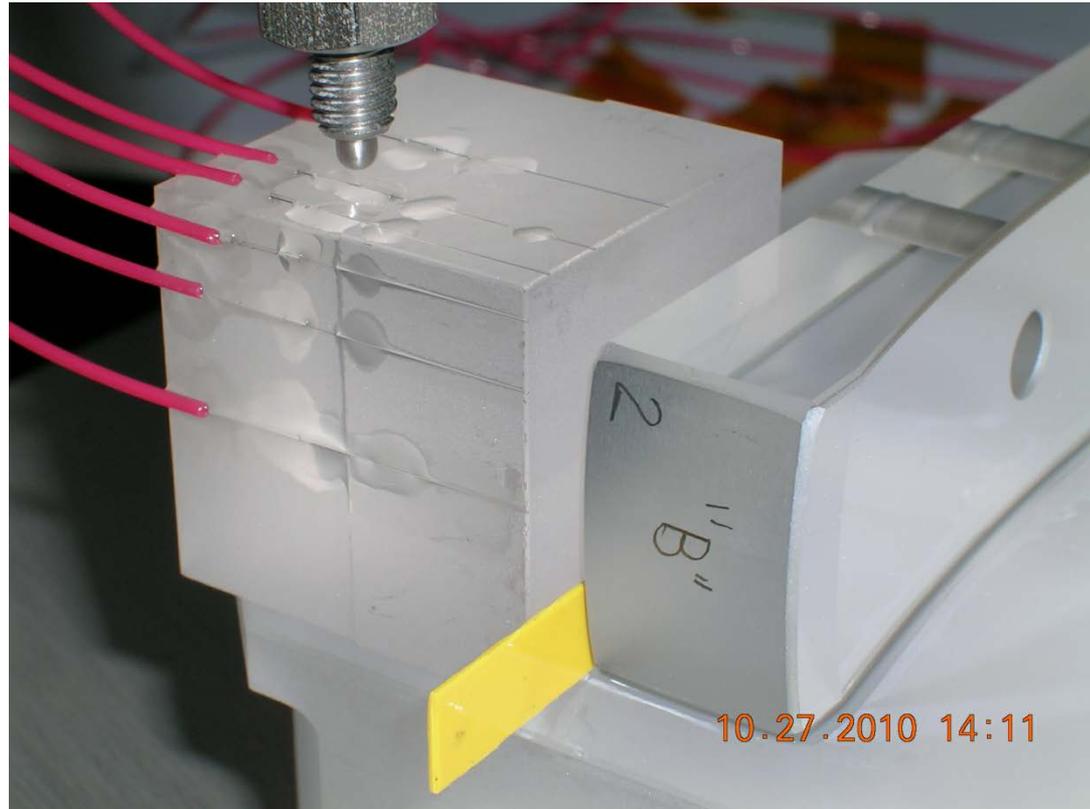
- **True PSF:** Image(x,y) at infinite spatial resolution.
- **Model PSF:** Our guess of what the true PSF is.
- **Pixelated PSF:** $I(i,j)$, the integral of $\text{Image}(x,y) \cdot \text{QE}_{i,j}(x,y) \cdot dx \cdot dy$

Classical Approach for centroiding:

- 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 $\text{QE}(x,y)$ within every pixel.
 - The canonical approach to measuring $\text{QE}(x,y)$ 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.

NEAT Approach for centroiding:

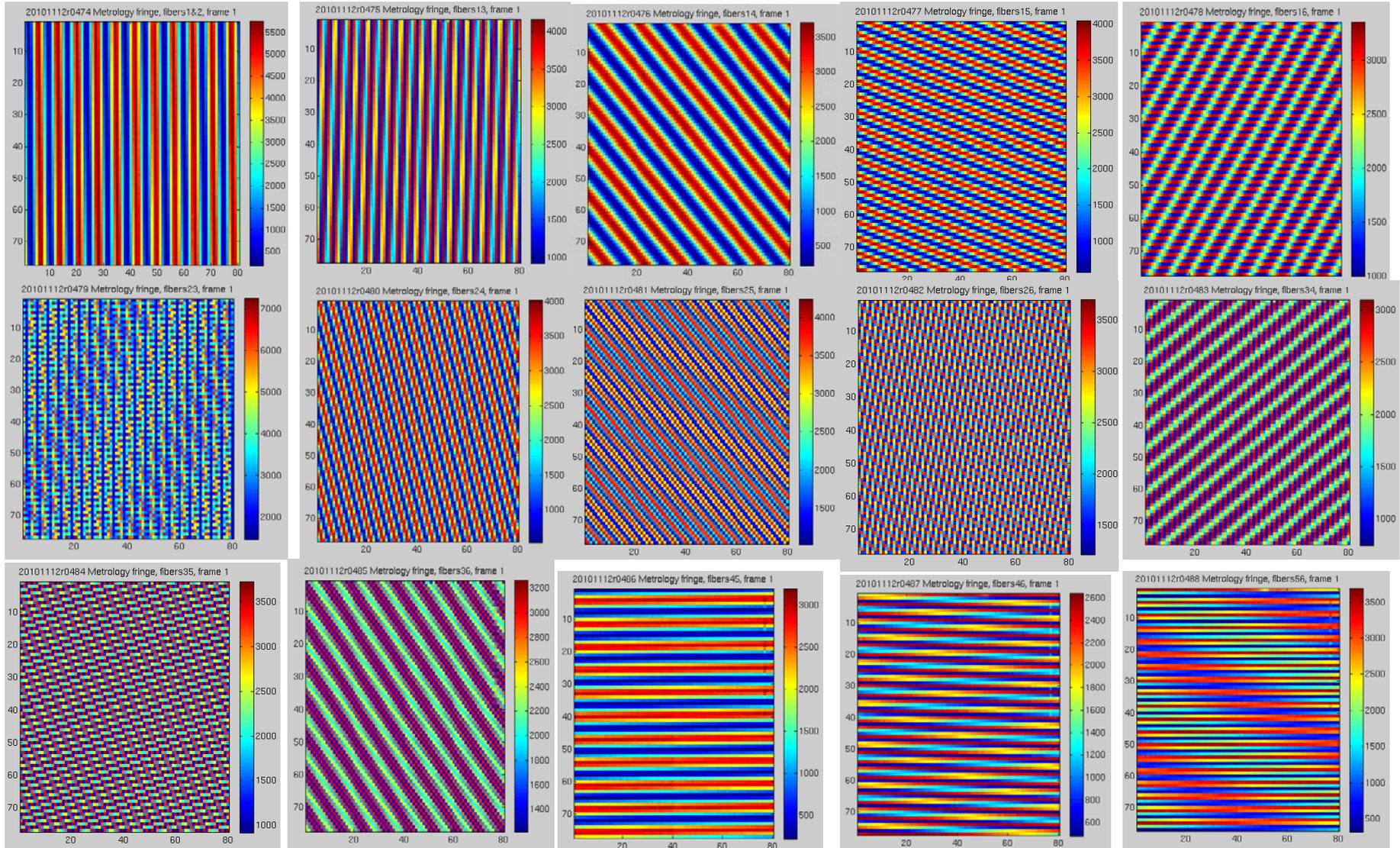
- **Nyquist** theorem: Critically sampling a band limited function at greater than $2 \cdot \text{bandwidth}$ is sufficient to **perfectly** reproduce that function.
 - We have the knowledge of the **true** PSF in the data, not a **guess** of the true PSF.
- We use laser metrology to measure $\text{QE}(x,y)$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

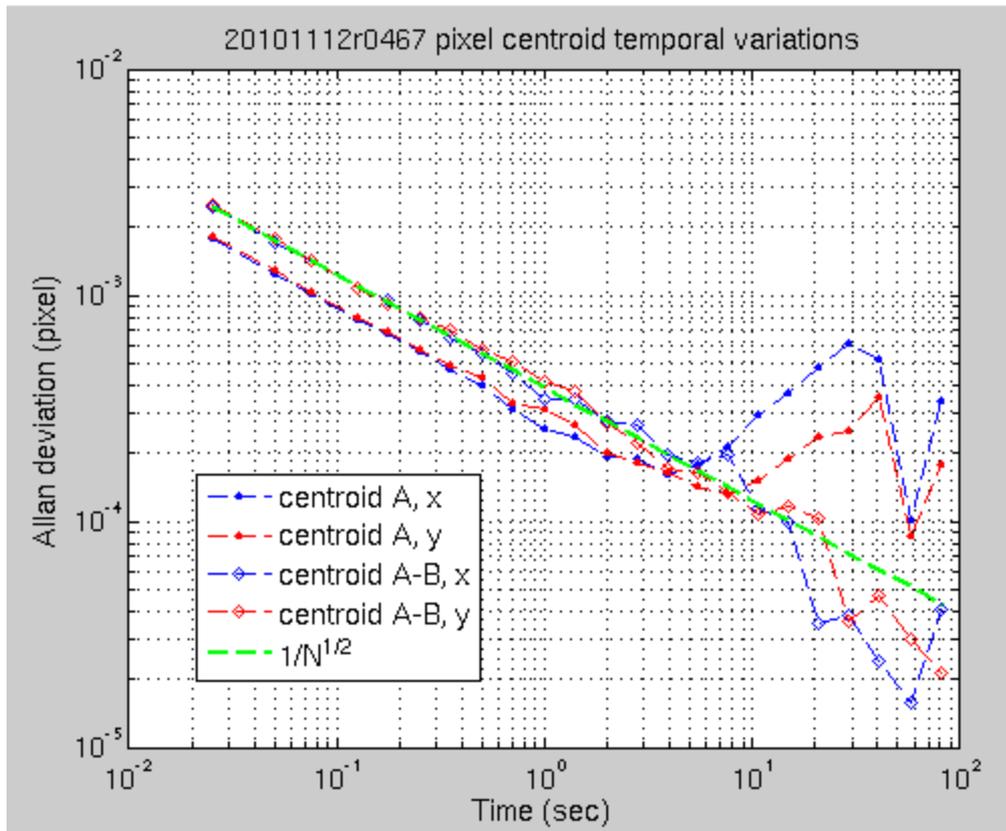


Sample Metrology Spatial Fringes





Centroid Allan Deviations

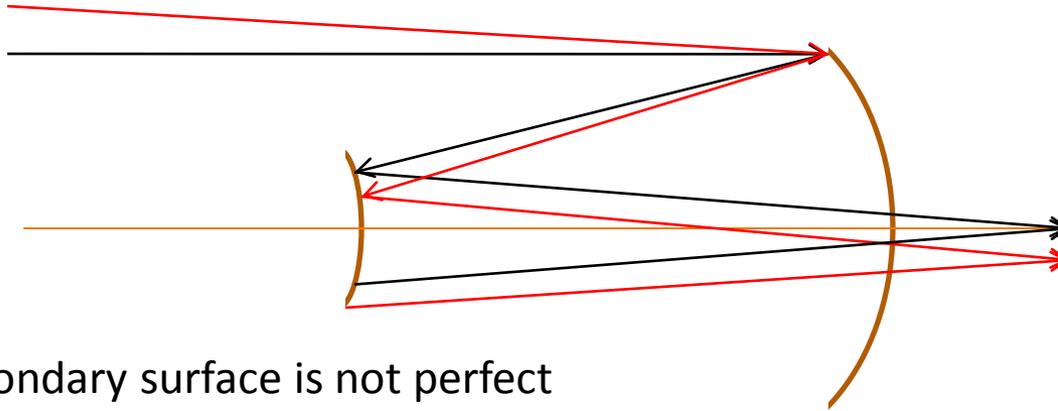


Single Fiber centroid reaches noise floor at $3e-4$ pixels (drift)
Differential centroid continue to average down to $\sim 4e-5$ pixels after 100 sec integration



Optical Errors

- Beam walk errors



- If the secondary surface is not perfect at the 5pm level there will be systematic biases $> 1\text{uas}$.
- 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 $\sim 10\text{uas}$ for 10 arcsec field.



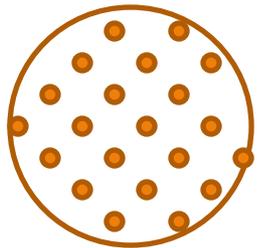
Calibration of Optical Distortion

- 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)
- If the optical distortion is highly unstable, changing minute by minute, then continuous calibration is needed.
- If the optical system (in space) is stable for many hours or days, but not stable for 5~10 YEARS, intermittent calibration may be adequate.

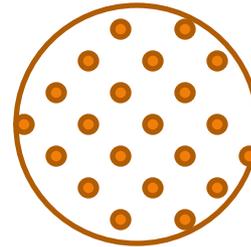
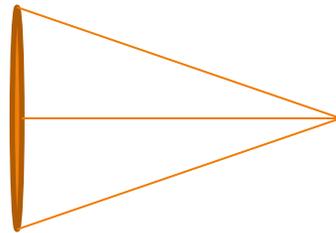


Diffraction Mask

- A regular array of dots in the pupil (in monochrome light) will produce a regular array of dots in the image plane.
 - The dots (black) on the primary mirror of the telescope should be stable over a long period of time. Warping of the primary produces changes in the PSF of the dots, but to 1st order the same change to all the dots in the image plane.



Regular pattern
In pupil



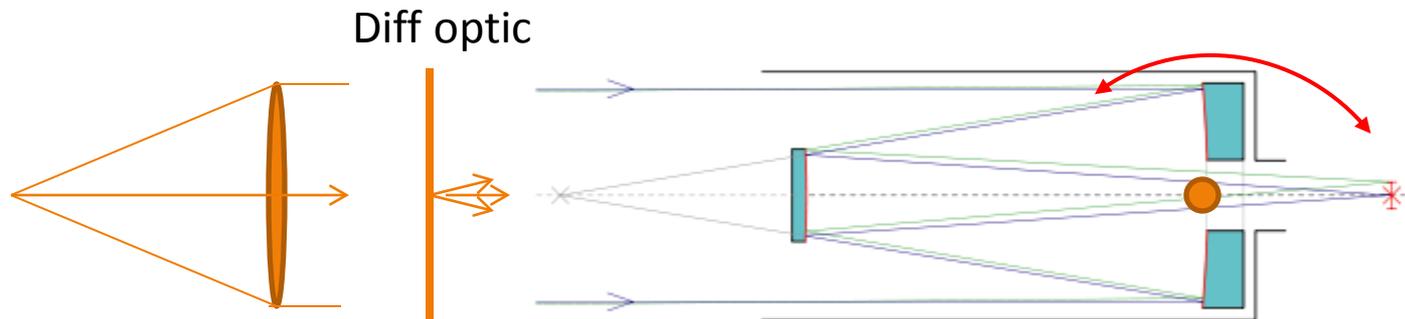
Regular pattern
In image plane

Lab test will be done with a mask fabricated by JPL's MDL Using e-beam lithograph on a 25cm glass disk. (MDL will fab a smaller ~5cm mask for Guyon)

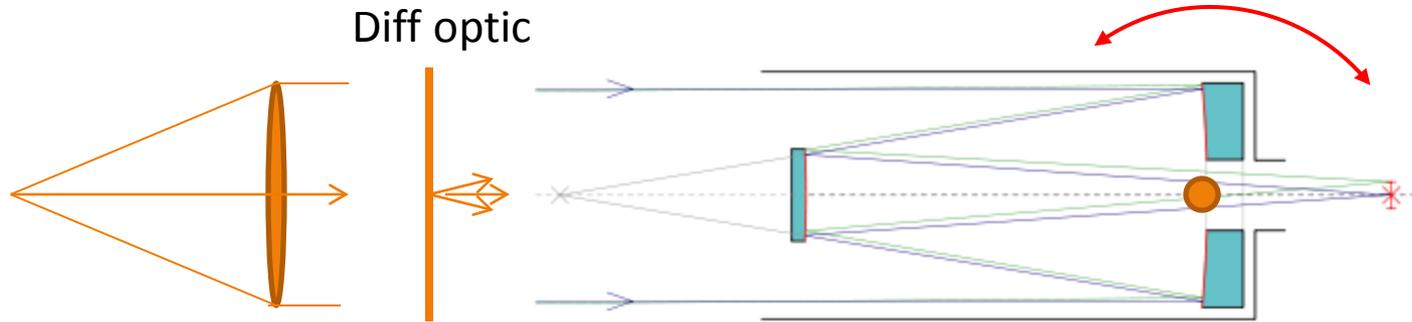


Lab Calibration of Field Distortion

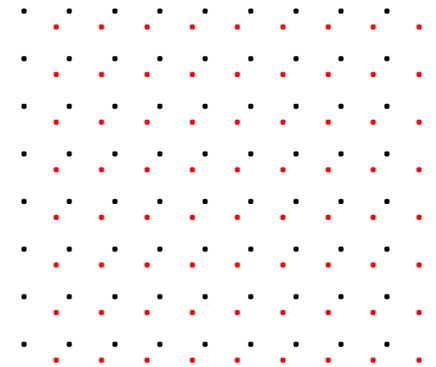
- Field distortion comes from
 - The optical design, (with perfect optics)
 - Imperfections in the optical figure (polishing error)
- Both errors are concentrated at low spatial freq. (Errors across 0.5 deg \gg errors across 0.001 deg. Numerical simulations by Guyon showed errors $\sim 10\mu\text{as}$ 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 $\sim 10\mu\text{as}$.





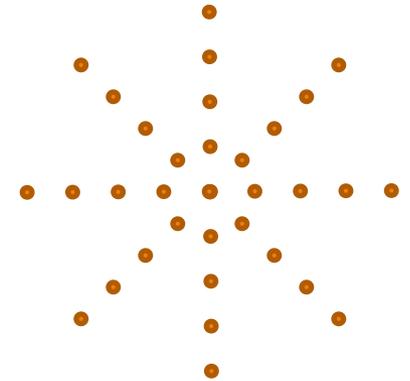
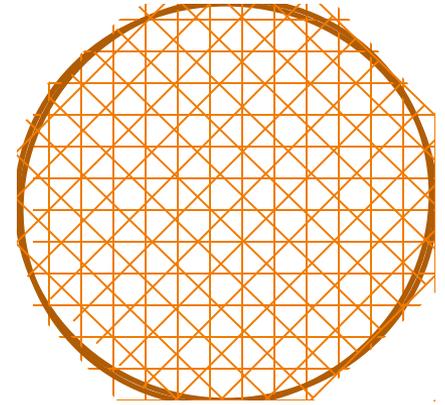
Ground Based Optical Navigation

- NASA's Deep Space Network (operated by JPL) is the primary tool for communicating with interplanetary spacecraft.
 - Optical communications (vs Radio) offers lower cost and higher bandwidth. NASA is considering a laser comm demonstration for the next Mars mission. (might fly as early as 2020).
 - A laser bearing spacecraft also offers the chance to test optical navigation. (Range, Doppler, angle(2)).
- The most accurate radio astrometry is (VLBI) with 0.2 mas accuracy. Over the next 2~3 years we hope to demonstrate ~1 mas astrometry relative to GAIA stars.
 - Activity just starting, an internally funded R&TD initiative for 3 yrs.



Hardware Upgrades

- Focal plane calibration of CCD.
 - 3~4 pixels per arcsec,
 - 4K² detector with pixel locations calibrated $\sim 3 \times 10^{-4}$ pixels.
- Pupil mask at front of telescope, with stripes in four directions. (incollaboration with O. Guyon, M. Ammons, E. Bendek who will be trying this at Lick)
- Diffraction pattern of strips in the focal plane will be used to calibrate the distortion of the optics.
 - The dots far from the center will broaden into radial spikes in white light.
 - Several approaches to calibrating optical distortion using the diffraction pattern.



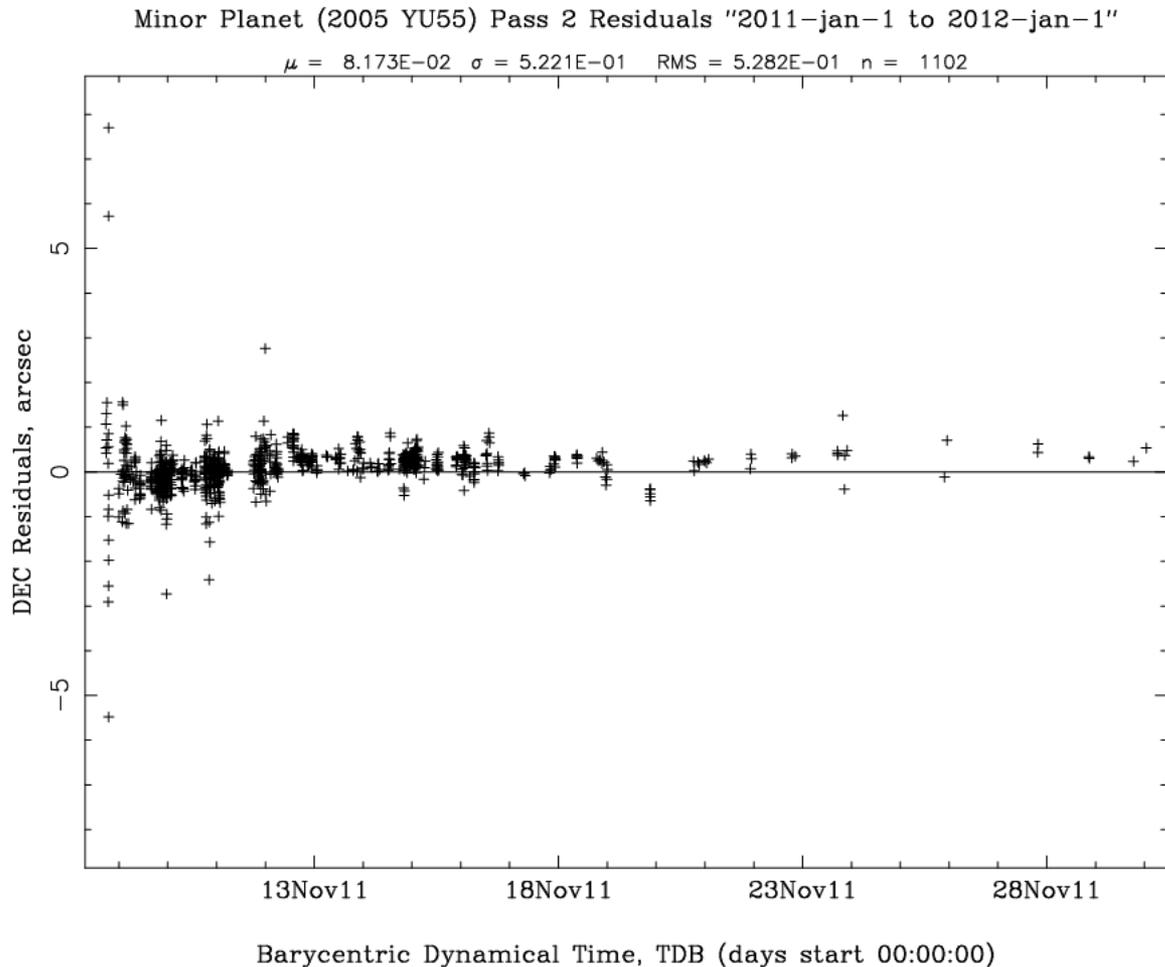


Software Upgrades

- Explicite DCR correction (along the lines of Pravdo, Shaklan)
 - Diff chromatic refraction can be $\sim 1\%$ of refraction for red vs blue stars.
15deg zenith angle \Rightarrow 150mas motion of blue vs red stars.
 - Observe same field at multiple zenith angles solve for DCR offset of each star.
- Incorporate CCD pixel calibration into centroid calculation
- Use preliminary GAIA catalog (versus UCAC) GAIA catalog may be available 16 months after Oct 2013 launch
- Test several methods of distortion calibration
 - Measure ref stars wrt diff pattern (azimuth) (Guyon approach)
 - Bright star's diff pattern at several locations in focal plane
 - Measure optical distortion vs HA, DEC, temp. (optical distortion will change with changes in the optical alignment of the telescope)



Orbits of NEOs with Optical and Radar Data



- ~ 1 year ago a large asteroid (300m) passed within 200,000km of the Earth.
- It was tracked optically (astrometry) as well as by the Goldstone Radar. (500KW 70m Xband, 3cm)
- The Radar data is **much** more precise than the optical data.
- At closest encounter, the error might be due to timing (internet time vs GPS time)
- RMS error outside of closest encounter 100~200 mas. Error source(s) not known
- DCR, Ref star catalog, OptDistort.

From J. Giorgini JPL

The ground optical navigation task is to demonstrate astrometry at the 1mas level (on NEOs) for future optical navigation of laser bearing spacecraft.



Summary

- We've started a series of lab experiments to demonstrate μ as level narrow angle astrometry for two applications
 - Spacecraft navigation. (needs 10^{-4} pixel accuracy) by measuring the position of 2 or more asteroids in the main belt against background stars in the GAIA catalog.
 - Astrophysics: (goal 10^{-5} pixel) narrow angle astrometry to find Earth sized planets around nearby stars, measure the masses of black holes with orbiting stellar companions etc.
- The 1st task is calibration of the focal plane to enable 10^{-5} pixel centroiding.
- The 2nd is calibration of optics field distortion at the μ as level, using diffractive optics. (field distortion calibration is not needed if the camera is a long focus telescope with a prime focus focal plane detector.)



Optical Distortion Calibration (Pupil Mask)

- Measure ref star position relative to nearby diff spots
 - Distortion is smaller on small angle scales. (one simulation by Guyon of the distortion from optical figure errors gave $\sim 10\mu\text{as}$ errors over a 20 arcsec field for state of the art optics 2nm rms)
 - Radial streaking in white light means this only calibrates azimuth distortion
- 2D calibration can be done by placing a bright star in 3 places in the focal plane.
 - Assume optical distortion is stable between calibration and science data taking.

