Technical Issues for Narrow Angle Astrometry (STEP)

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Outline

- Ground based narrow angle astrometry
  - Current state of the art (0.5~1 mas (in 30 min)
- What are the limiting error sources
  - Photon noise (field of view)
  - Optics errors (field distortion, beam walk)
  - Detector errors (imperfections in CCDs)
  - Centroiding algorithms
- The final goal (an instrument whose accuracy is primarily limited by photon noise.

Current State of the Art (ground based)

- Narrow angle astrometry on the Palomar 5m telescope. (China has access to the Palomar 5m telescope)
  - Pravdo, Shaklin
- Carnegie (Boss et. al.)
  - http://instrumentation.obs.carnegiescience.edu/ccd/caps.html
  - 2009PASP..121.1218B
- Both groups have gotten ~ 0.3 ~ 1.0 mas in a ~30min observation. The science goal of both groups is exoplanets.
- Pravdo et. al. in 2009, published the discovery of a super Jupiter around the brown dwarf VB10. (this was a ~ 6 sigma detection) Unfortunately it turned out to be false. The planet should have produced a detectable RV signature, and ~6 months later that RV signature was found to be absent.
- Space based narrow angle astrometry (STEP) aims to get ~1uas precision, 300 times better that what's possible on the ground, (due to atmospheric turbulence)

Photon Noise

- Nominal 1m telescope 0.36 sqdeg fov
  - 0.71 uas in 1 hr (photon limit from ref stars)
  - SIM-Lite performance 1.0 uas 2axis, in 1 hr

	1m	1.4m
0.4 deg	0.94 uas	0.48
0.6 deg	0.71	0.36
0.8 deg	0.58	0.29 uas

R band 640nm 25% bw
Total QE 60% (ideal 85%)
Use photons from brightest 6 ref stars
ref stars (avg for sky from AQ4)

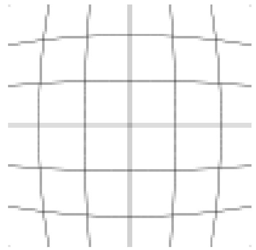
#ref stars	5	6	7	10	100
phot noise	0.73	0.71	0.69	0.65	0.52 uas
faintest	11	11	11	12	14 mag

CCD can run at 25C (but very slightly better at 0C)

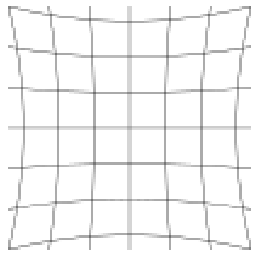
If target star < 8 mag, photon noise from target not important
Photon noise from laser metrology not important.
Lasers turned on ~3% of time, every ~ minute (depending on therm stab)

Telescope Field Distortion

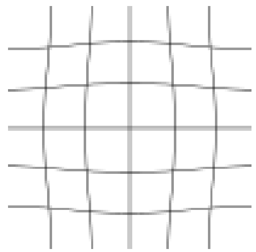
- For a perfect telescope, there is no distortion. But no telescope is perfect.
- 100 years ago, astrometric telescopes were long focus refractors. (60cm dia f/16)
- Modern telescope are all reflectors with fast (f/1.5) primaries. Even the Palomar 5m, has an f/3 primary.
- Field distortion is closely tied to beam walk errors that would be a major source of error in space astrometric telescopes.



Barrel distortion



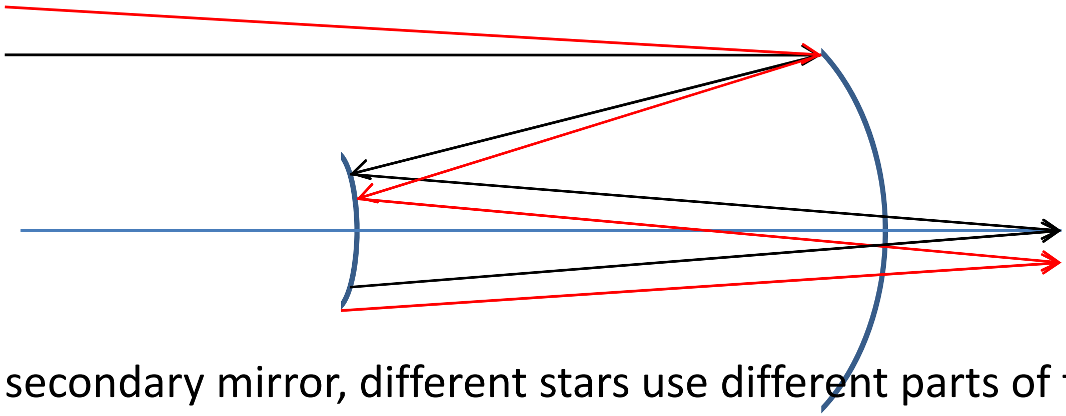
Pincushion distortion



Mustache distortion

Beam Walk Error in Normal Telescope

- Light from all stars hit the primary mirror. Errors in the primary mirror cause the image to be slightly distorted, but this distortion is the same for every star.



•But at the secondary mirror, different stars use different parts of the optic. Light from off axis stars “walk” across the secondary mirror.

•If the secondary surface is not perfect, there will be an astrometric error.

•Even if the optics are perfect, If the alignment of the telescope changes there can be an astrometric error. (This error can be ~10 mas over a 10 arcmin field of view on a normal telescope)

Detector Error

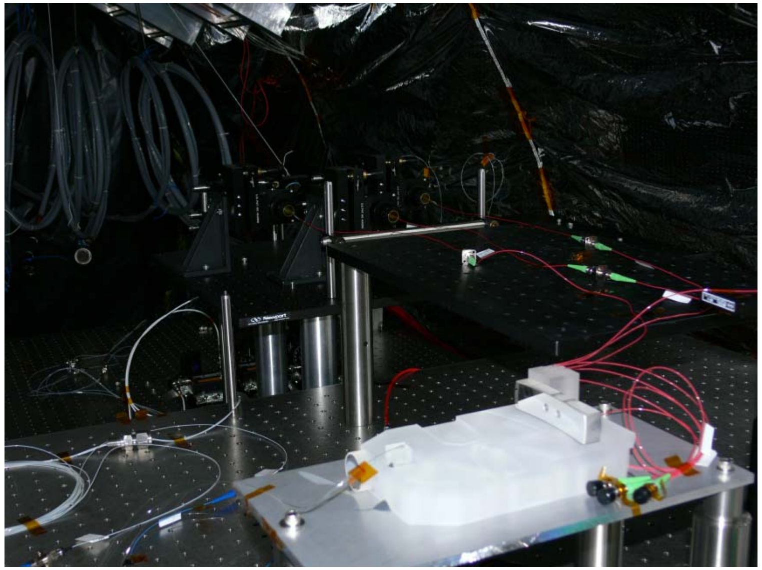
- In space where one is worried about 1 uas astrometry, and centroiding a stellar image to 10^{-5} λ/D, detector imperfections are extremely important.
- On the ground if the final goal is 300uas, and the star image is 1arcsec spread over 5 pixels, we need to centroid the star to about 1/1000 pixel.
  – Normal CCDs (15um) have pixel placement errors ~ 50nm. ~1/300 pixel. So some calibration of the CCD geometry is needed but nowhere near what is needed for space.

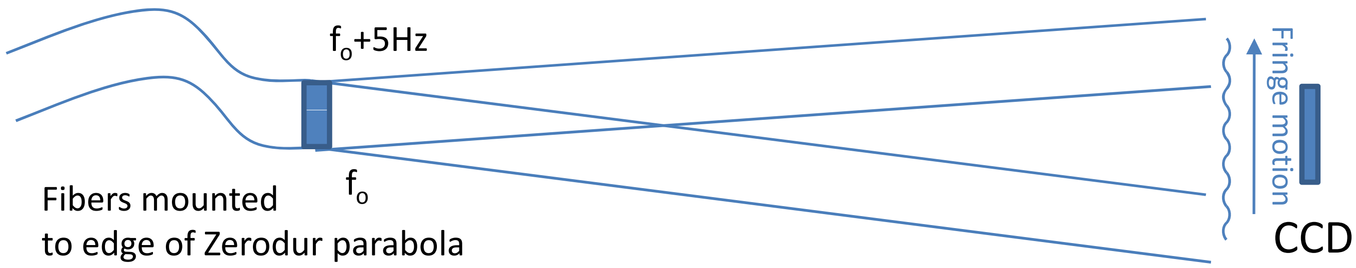
Calibrating CCD Centroiding Errors

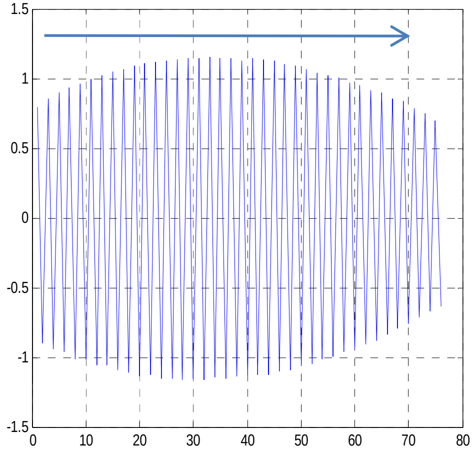
- Two classes of errors
  - Pixels move. Measure location of a group of pixels
- PSF centroiding with imperfect pixels
  - QE(x,y,I,j) Intrapixel QE spatial variations for each pixel.
  - Deriving Optical PSF shape
- Simulations of PSF centroiding, assumptions, and how detailed do we have to know the PSF and the QE(x,y) to centroid to ~5e-6 pixels, and how do we make the calibration measurements?
- Initial CCD centroiding results.

Micropixel Centroid Tesbed I Pixel Position

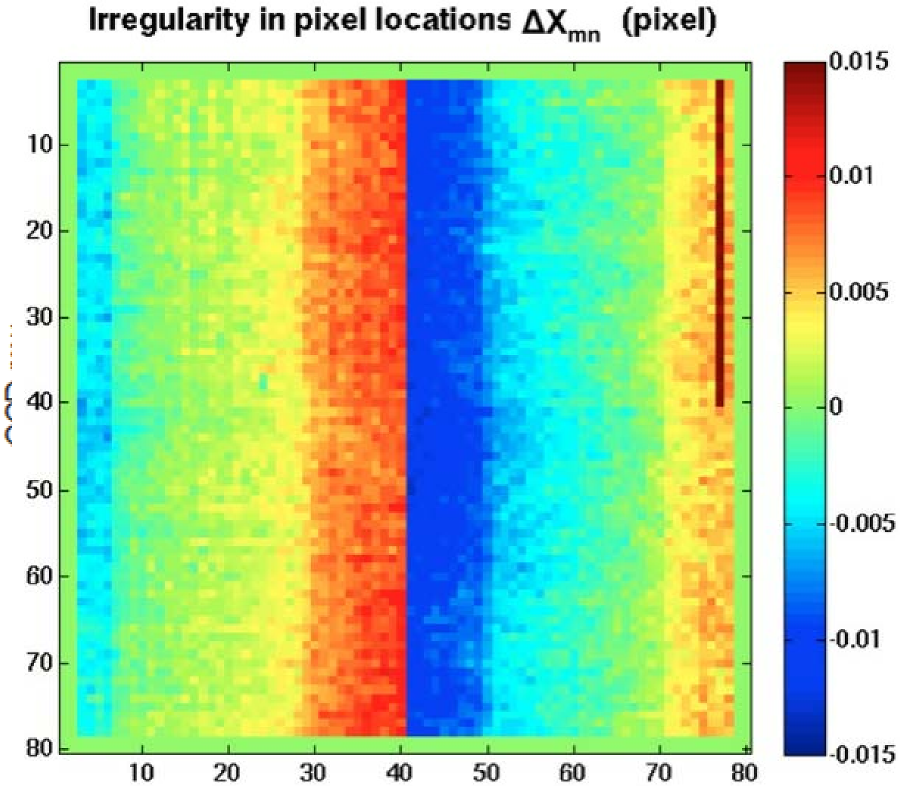
- 10^{-5} pixel centroid measurements are needed for 1uas astrometry. Current state of the art is about ~$2x10^{-3}$ pixel.
- The graph shows the spatial fringes across 80pixels.
- The fringes move (left to right) at ~5hz, images are recorded at 50hz.
  - If the fringe motion is uniform, then one pixel's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

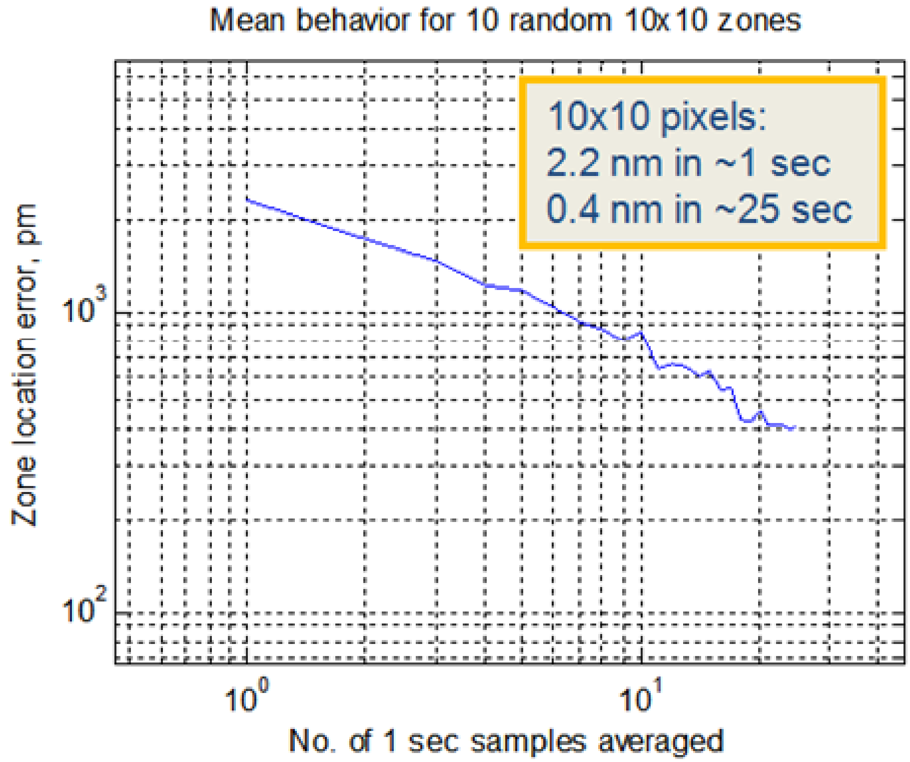






Testbed Results: Measuring Pixel Motion

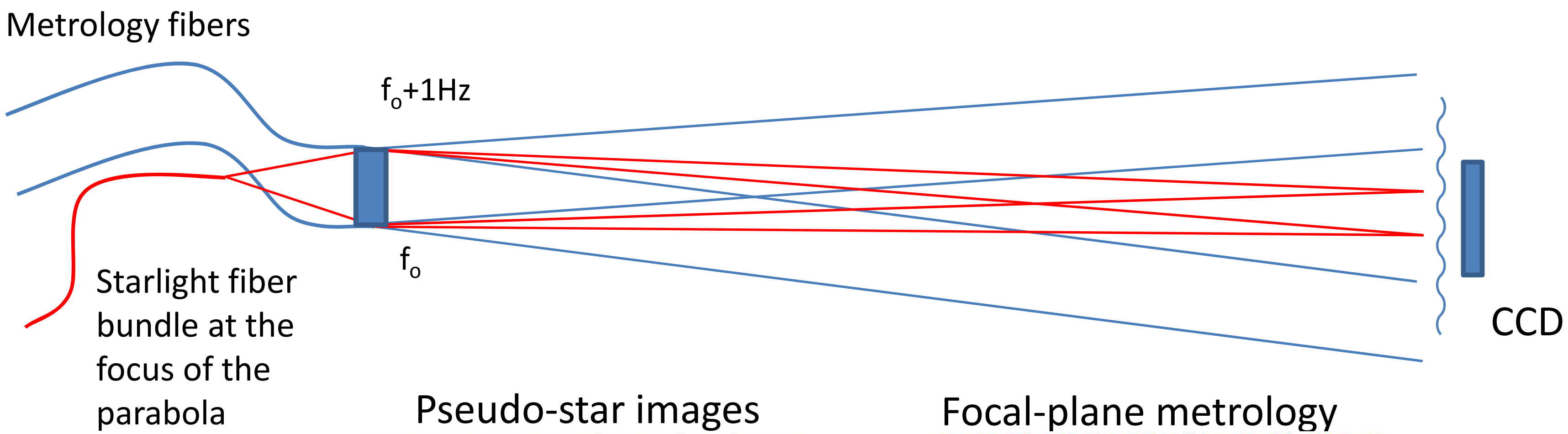




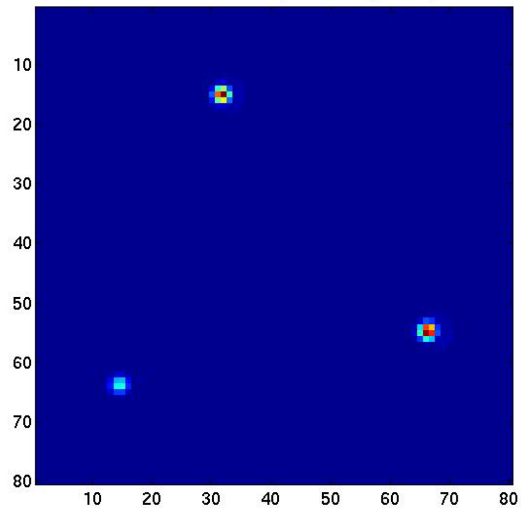
- If we were to fit a static fringe pattern across many pixels, the QE variations that are unknown would bias the pixel position.
- Instead, with heterodyne fringes, we measure the position of a pixel by looking at that pixel's flux versus time (phase of a sine wave in time).
- **We have demonstrated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

Testbed: Next Step

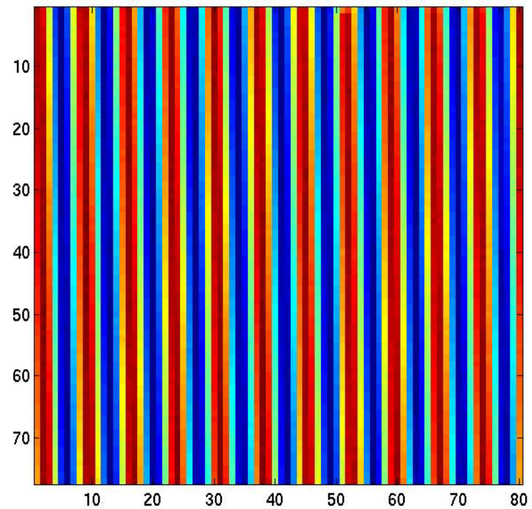
- Conduct 2D (X,Y) measurements of pixel position.
- Put pseudo-star images on the CCD and demonstrate centroiding to 10^{-5} pixels.



Pseudo-star images



Focal-plane metrology



Star Centroiding to 10^{-5} pixel

For ground based astrometry
Centroidig to 10^{-3} pixel sufficient

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 Image(x,y)·$QE_{i,j}$(x,y)·dx·dy

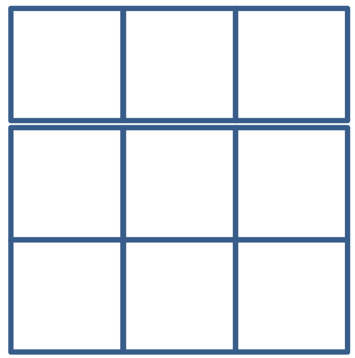
Classical Approach for centroiding:

- 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 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.

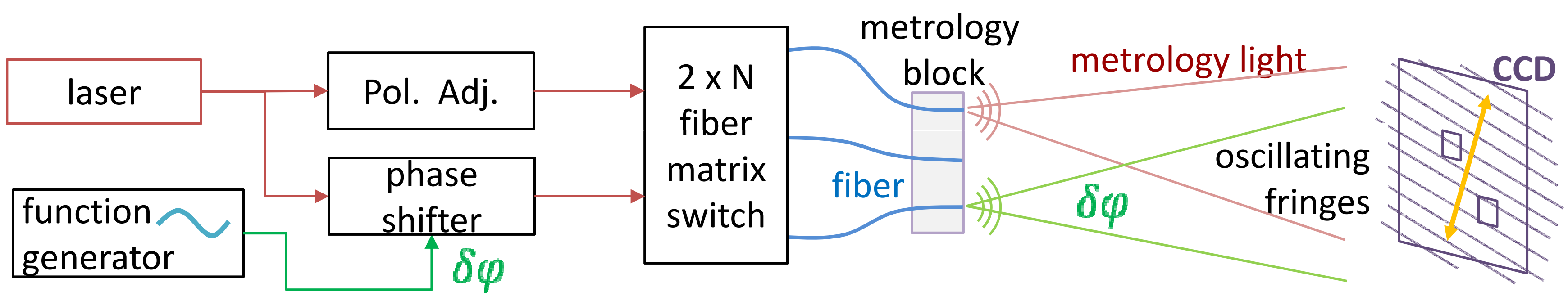
NEAT Approach for centroiding:

- **Nyquist** theorem: Critically sampling a band limited function at greater than 2*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 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.

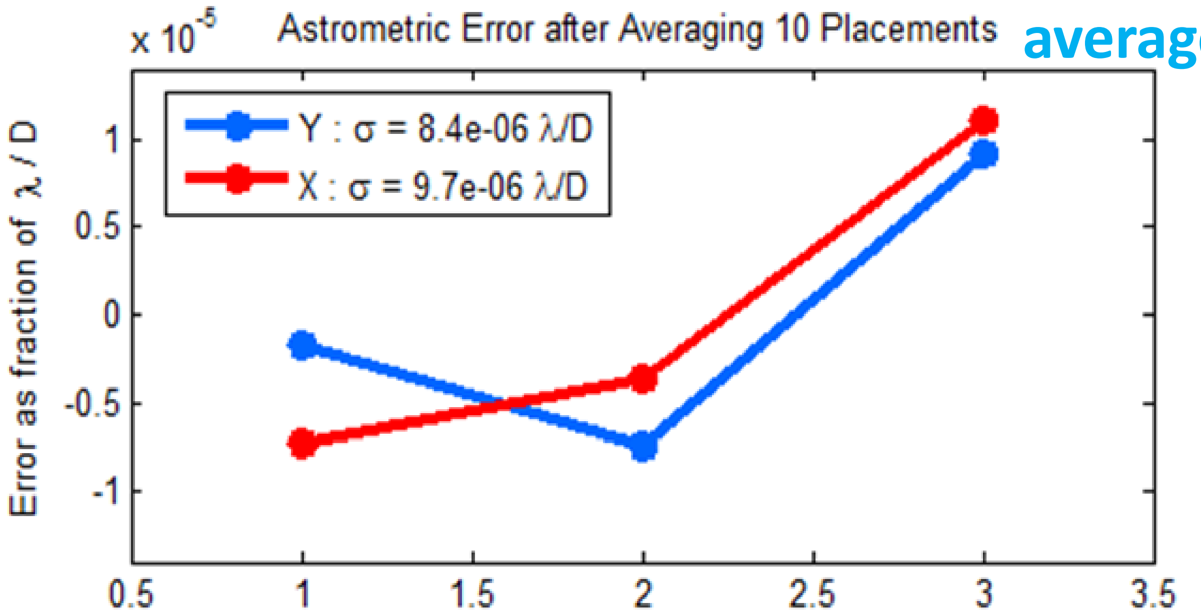
Measuring Intrapixel QE variations

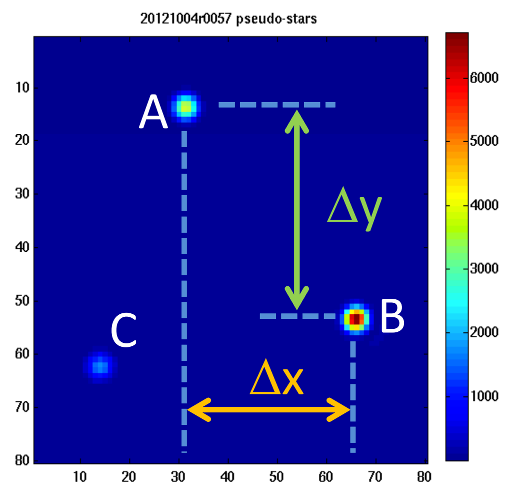


CCD calibration and centroiding to ~10^{-5} λ/D



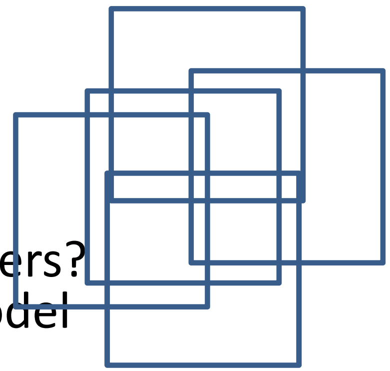
Lab Performance:
average error of 9e-6 λ/D





Field Distortion Calibration

- Standard technique, take multiple images of the same star field, displaced by a fraction of the FOV.
- Model the distortion (eg polynomial) and solve for the model coefficients from the multiple images
- How well should this work?
  - Field distortion calibration can't be better than the calibration of the detector.
  - Does the model have a sufficient number of parameters? (with perfect optics and a large f/# telescope, the model doesn't need many parameters. But if the optics has figure (polishing) errors, the model may need 100's of parameters.
  - Is the field distortion constant in time?
    - Is the optical figure stable (gravity, thermal)
    - Is the alignment of the telescope/det stable with gravity loading and thermal change.

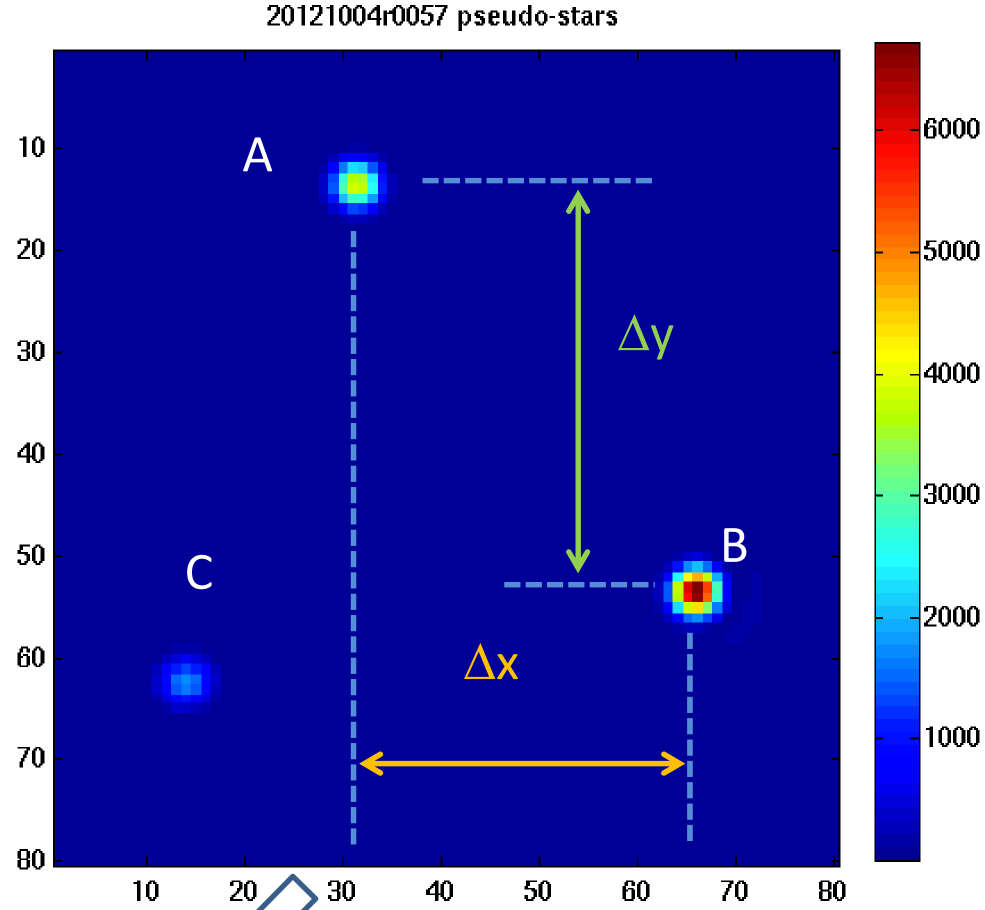


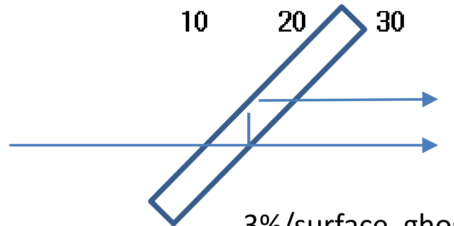
Ground Astrometry

- Dynamic range problem. New detectors (EM-CCD, SCMOS) have very low read noise. There is almost no penalty to reading them "fast", this way the bright stars are not saturated, and the dim reference stars can get high SNR by co-adding many images.
- GAIA will produce a preliminary catalog by ~ june 2015. This will provide positions of 10^9 stars with < 1mas accuracy. (in 2020 GAIA's catalog will be ~10uas for the brightest ~50 million stars) This catalog will simplify field distortion calibration. Can use a single image to calibrate distortion.
- Atmospheric turbulence. If the instrumental errors are calibrated the atmosphere will present the ultimate limit. But the limitation should be slightly below 1 mas (for ~0.5 hr observation)

Unexpected Error Sources

- Optically there were only 3 star images on the detector. (unfortunately not visible in this picture) there were a number of “ghost images” at levels ~10^{-3}~10^{-4} below these three images.
- As we moved these 3 images across the CCD, the ghost image moved but often in the opposite direction. We looked for optical ghost reflections (from windows etc) found none.
- Our French colleagues also saw the ghost image. (their optical set up we totally different.
- Eventually we concluded the problem was electrical Xtalk on the CCD chip. (common to E2V39s





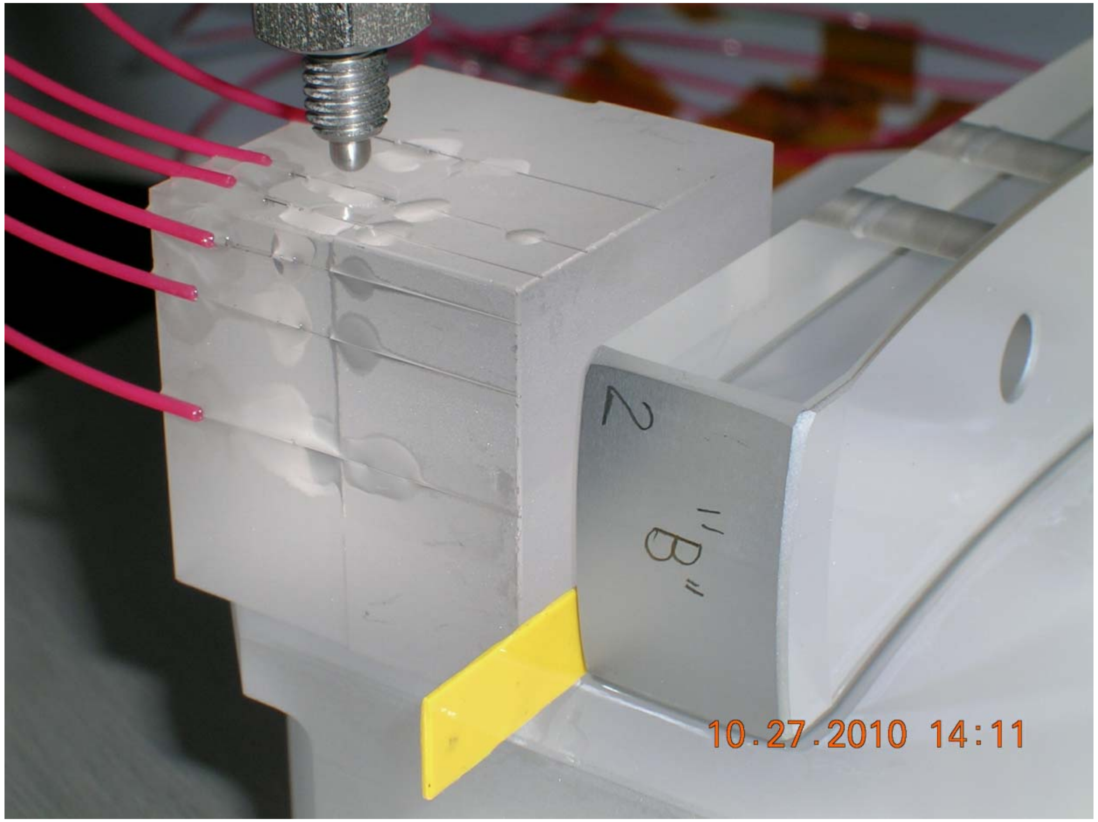
3%/surface ghost ~10^{-3}

Summary

- Space astrometry offers a potential improvement of ~300X over ground, because there is no atmosphere.
- But many systematic errors must be controlled /calibrated /eliminated.
  - Detector errors
  - Field distortion and beam walk (optical errors)
- Very high astrometric accuracy is possible with a modest cost (~1m dia telescope)

Photon Noise is Not an Issue
What's the Best Astrometry with a Telescope?

- Ground based astrometry is limited by atmospheric turbulence
- In Space, HST astrometry (with CCD camera) is perhaps the most accurate. ~100uas. (λ/D ~40mas, critically sampled, 1/200 pixel)
- With NEAT we hope to do 1uas (in 1 hr) with a 1m telescope.
  - 100X higher accuracy with ½ smaller telescope
  - Centroid to 1/50,000 pixel
- How is this possible? (this is the wrong question to ask) The right question is what are the systematic errors that prevent HST from doing 1uas astrometry.



- 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 ~2×10^{-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