MicroArcsec Astrometry Techniques

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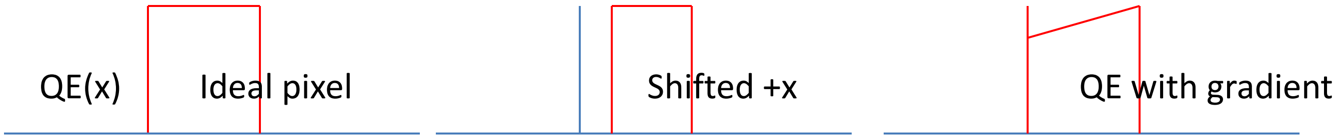
Conf on Future Space Mission with Very High Accuracy Astrometry

Outline

- Error sources at the uas level and the mitigation
  - Detector imperfections
    - What are the imperfections, how they can be calibrated
    - What type of detectors can't be calibrated
  - Optical sources of astrometric errors
  - Observing very bright sources and much fainter reference stars at the same time.

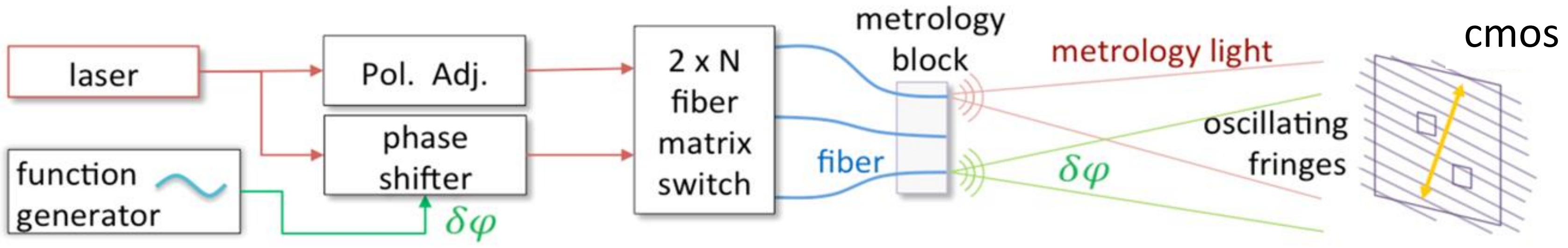
Detector Errors

- A space telescope with a ~1m aperture has a diff limited PSF ~0.1 arcsec FWHM. This PSF should be sampled with a detector at least 2 pixels (per λ/D 1 pixel ~ 50mas) 1 uas accuracy means centroiding the PSF to 1/50,000 of a pixel. For a detector with 5um pixels this means centroiding to ~0.1nm. This level of accuracy is beyond current chip making technology.
  - The only recourse is to calibrate the fabrication errors.
- Pixel position error and QE non-uniformity across an individual pixel are two sides of the same coin.



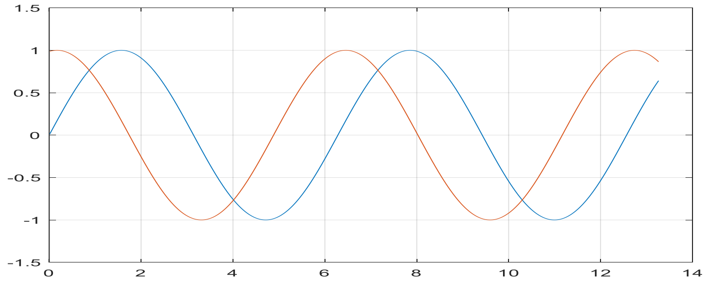
- PSF multiplied by QE(x,y) is the photometric signal from that pixel. QE(x,y) can be quite complex, but if you think of this in the fourier domain, If the PSF does not have an spatial freq content above 1 cycle/(lamda/D) This is why measuring the pixels position is sufficient to allow centroiding to very high accuacy.

Measuring Pixel Position

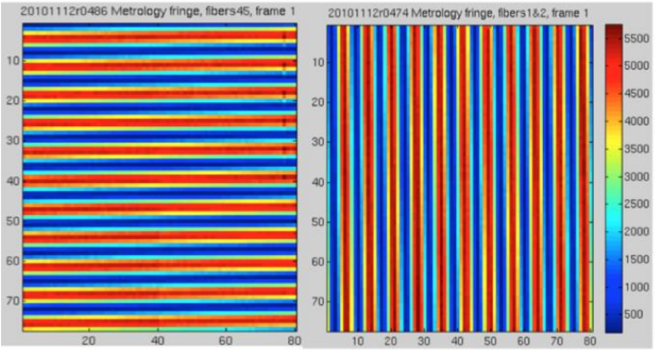


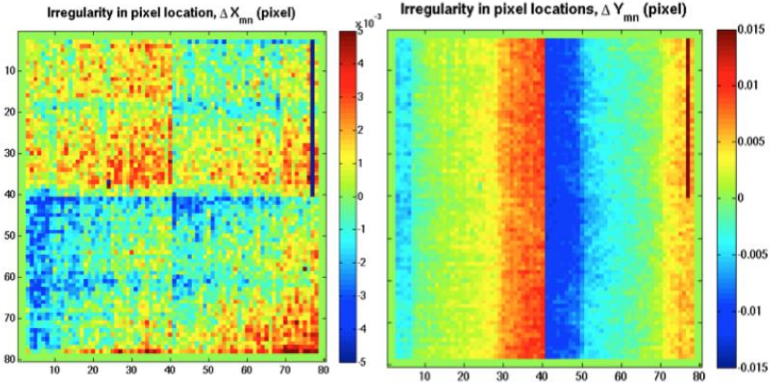
Laser light from two single mode optical fibers 1-2m from the detector form fringes that illuminate the whole detector. The wavefront is a nearly perfect spherical wavefront.
The fringes using a phase shifter are moved across the detector.

A simple way to understand this is to envision the fringes moving across the detector at 1Hz. The photometric output of the pixels is also 1hz and the phase diff between the sine waves is a measure of The separation between those 2 pixels.



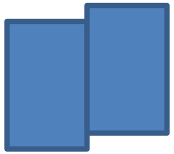
Early Experiments





Horr, vert fringe on E2V39 CCD

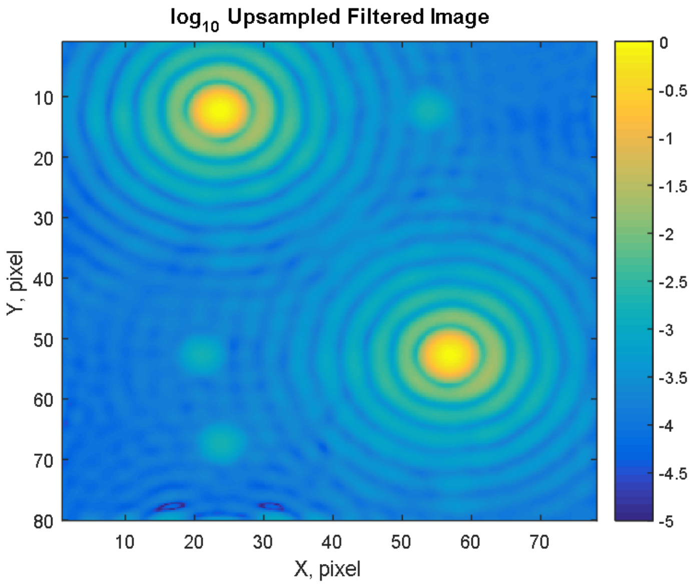
DelX, DelY pix error map
This particular chip had a very large ΔY displacement of ~700nm (24um pix)



Randomizing Pixel Errors

- Typical pixel position errors on CMOS/CCD imagers are ~ 1% of a pixel. Since a few dozen pixels are used to centroid a star, if the pixel positions are random, the centroid error would be ~3E-3 pixels. By moving the stars across the FOV, one can further drive down pixel position errors if they are random. (HST has used this technique by streaking the field in X then in Y.)
- Still it's impractical dither the star field to 10^6 positions to get to uas levels. In addition detectors will have large scale systematic errors that won't average down as sqrt(N) forever.
- However after calibrating the pixel positions to the uas level, the residual errors should be moderately random and we should use the same approach, moving the star field around to pick up ~10X reduction in pixel position errors.

Applying dx,dy into astrometry

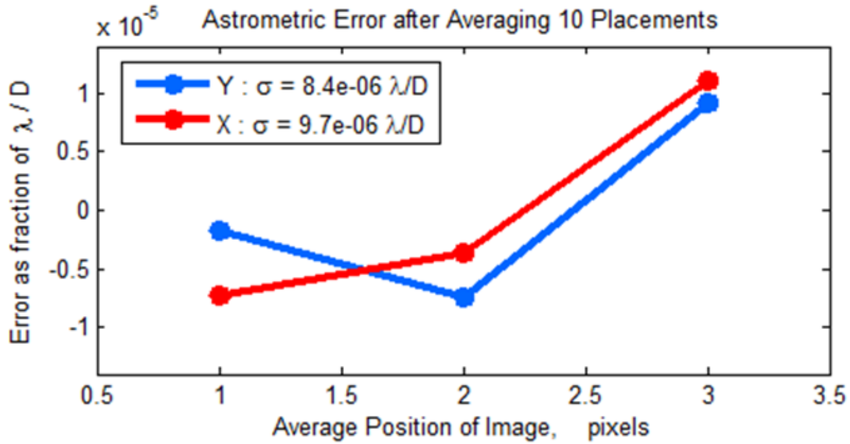


Normal astrometry centroids a star in a least sq fit

Var = Σ (data(i,j) – model(i,j, x, y))^2 (x,y is centroid of PSF)

This equation doesn't have a place for the pixel position errors measured by the metrology system.

The equation has to be expanded so the model includes the dx,dy pixel position errors. Still solving for x,y centroid.



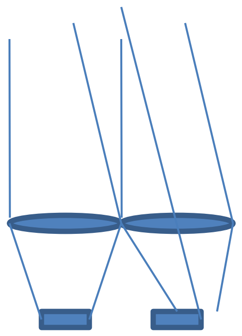
Electronic ghost images

From Xtalk of the 4 read amps

On the CCD.

What Devices can/can't be calibrated

- The centroid of a PSF usually involves the photometric values of ~1/2 to a dozen pixels.
  - The device should be linear to better than 10^{-3}. Many CMOS sensors achieve large dynamic range (16bits) by using a high gain 11~12 bit A/D and a low gain 11~12 bit A/D and combining the outputs digitally. Often with error >> 0.1%.
  - CMOS sensors with lenslet arrays are not calibratable, the reason is that the pixel's QE(x) is a function of both x and θ
  - Somebackside thinned CMOS (and CCDs) are too thin, and exhibit etaloning. (QE again a function of angle) (~40 um)

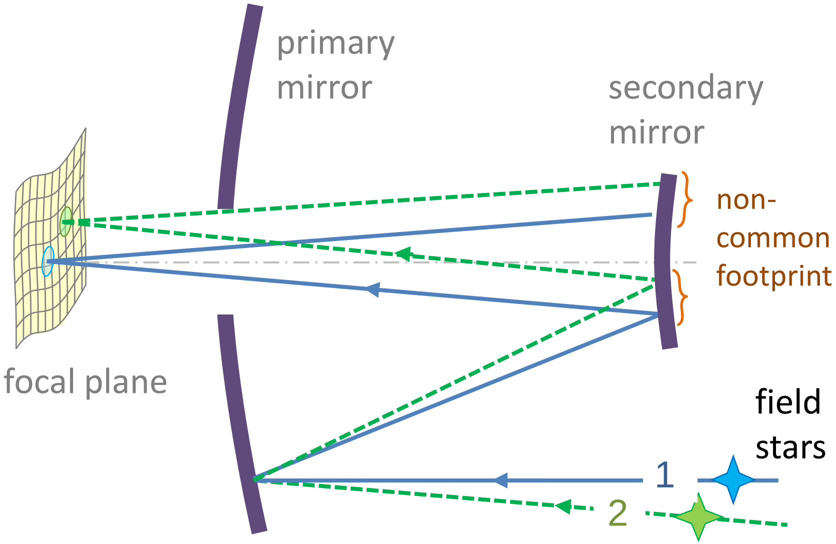


Many, otherwise excellent Sony Cmos detector have lenslet arrays, even backside CMOS
Several E2V cmos devices (for UV) are too thin.

Calibration of Optical Distortion

- All telescopes have distortion. There's distortion in the design. The distortion is slightly different if the optical elements are slightly misaligned. And finally, beam walk combined with the imperfect ($\lambda/20$) fabrication of the optical surfaces.
  - The usual approach to removing distortion is to use multiple reference stars and solve for the distortion terms. The question is how many reference stars are needed, to remove distortion at the ~ 1uas level?
- We try to answer this question with a series of simulations.
  - A detailed ray trace model with perfectly fabricated optics, but with slight misalignments. And the add to that astrometric errors caused by optical polishing errors at ($\lambda/20$) combined with beam walk.

Optical Distorton (Model/Assumptions)



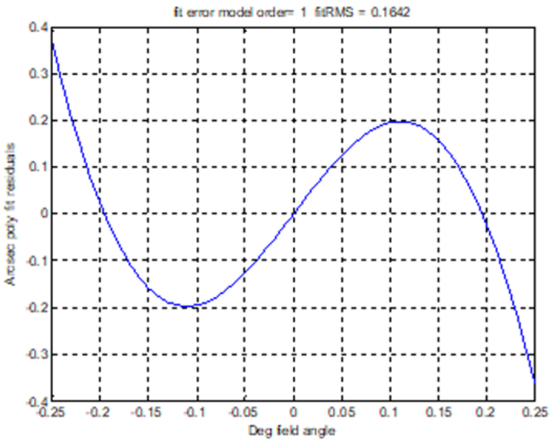
Wavefront errors on the primary of the telescope are common to all the stars, and do not introduce distortion errors. At one time

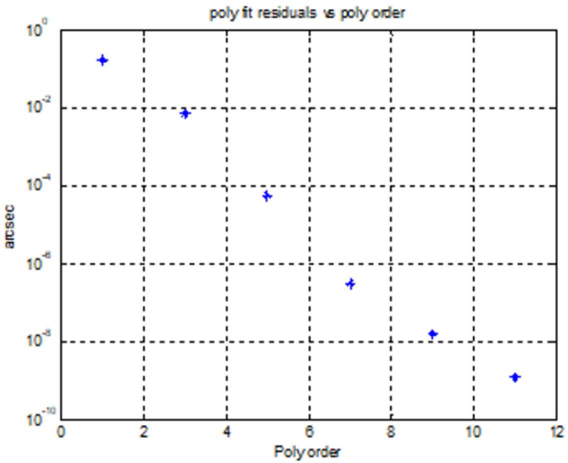
The ray trace model assumes perfectly fabricated optics that might be slightly misaligned. And calculates the centroid of many stars across the field of view.

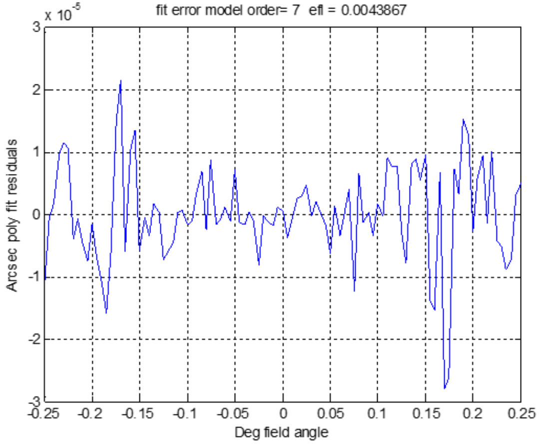
The beam walk/wavefront model (currently) only looks at the optic where the beam walk is the largest. We assume the wavefront error on that surface has an error of $\lambda/100$ rms (equiv $\lambda/20$ p-v). The wavefront error is propagated to the focal plane where its centroided.
Key assumption is that the power spectrum of the wavefront errors obey a $1/f^3$ power law.

Optics Field Distortion

- Also we found that $\lambda/20$ optical figure errors are also well modeld by the 9th order poly. (optic closes to focal has the most beam walk)
  - Made errors ~2X worse with $\lambda/20$
- Chromatic errors were dealt with by limiting spectrum to 500~750nm. And designing the system accordingly.
  - What matters is shift in position when star's temperature changes. (offsets don't matter because we're looking for periodic motion)
- Modeling to 9~10th order implies we have ~ 100 reference stars.

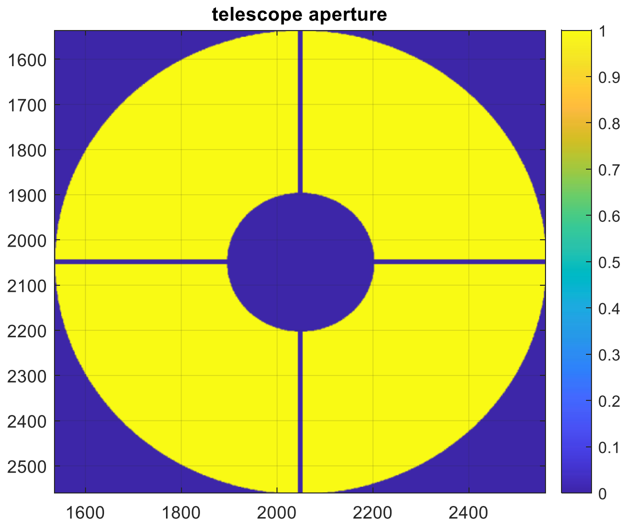


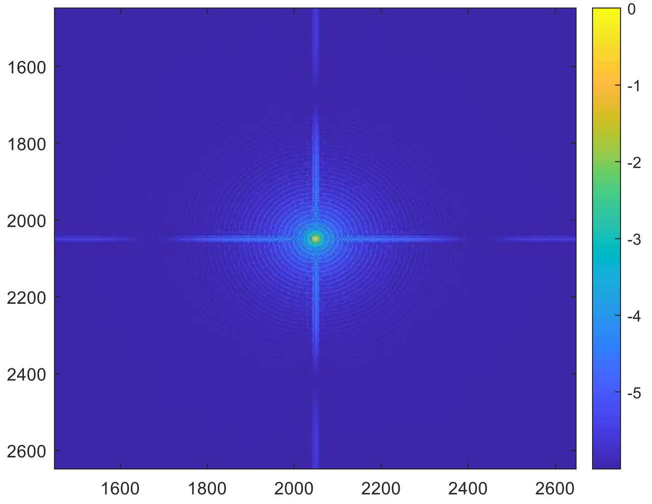




Astrometry of Very Bright Objects

- For a narrow angle (0.5 deg) FOV telesocpe, the typical 100~300 ref stars would be from 8mag to 14 mag. If the target star is very bright (0~3mag) it will saturate the detector if we hope to also detect 14mag stars above the readnoise.
- A technique that's been used with some success is to centroid on the diff spikes of the star rather than the saturated core of the bright star.





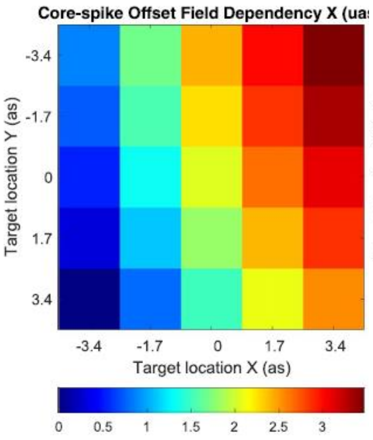
However because of wavefront errors, the centroid of the diff spikes is **not** exactly the same as the centroid of the core of the difffraction limited image. For l/20 wavefront errors, the core/spike offset on a large space telescope ~100uas.

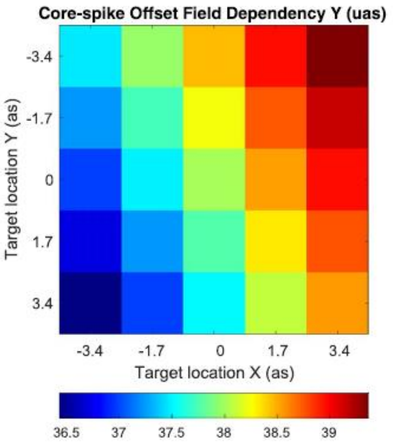
Modeling Core-Spike offset

- The wavefront error produces a bias in the core image that is slightly different than the bias in the spike centroid. (The core centroid offset is modeled with ref stars). But the spike centroid is not. And the core-spike offset changes over the FOV.
- The core-spike offset can change by ~3uas if the target star move ~6 arcsec across the FOV.

Table 3
Centroid Offsets Due to Wave front Aberrations

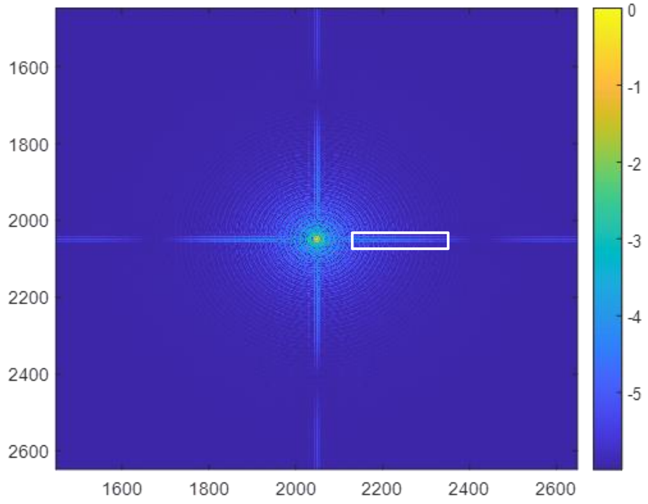
	X (μas)	Y (μas)	R (μas)
Core centroid	787.34	−407.69	884.64
Diff spike	663.38	−180.96	687.61
Core-spike offset	123.97	−226.74	258.42





Calibrating Core-Spike in Space

- Core-Spike offset is due wavefront errors. Which will change when the telescope is in space so the offset calibration will have to be done at several points over ~10arcsec*10as in the (~0.5 deg FOV).
- The calibration is straightforward. Take very short exposures (usec) where the core does not saturate co-add 100's of 1000's of them get enoughSNR for the spikes to be centroided at the sub uas level. Repeat at ~dozens times over a 10*10 arcsec field.



- What's the PSF for centroiding diff spikes?
- The PSF for both the core and the spike is the diff limited PSF in the absence of wavefront errors.
- When the pupil has no phase errors the core centroid and the spike centroid are exactly the same. (the FFT of a real function is symmetric)

Summary

- We describe what we think are the major technical obstacles to obtaining microarcsec astrometry with moderate/large space telescopes and possible solutions to these problems.
- The photons from stars are perfect but as soon as those photons touch an optical surface or a detector numerous instrumental errors are introduced.
- Calibrating both detector errors and optical errors is the key to getting to 1uas and below.
- And we can make use of the diff spikes to do astrometry of very bright objects against reference stars that are ~1000 times fainter.