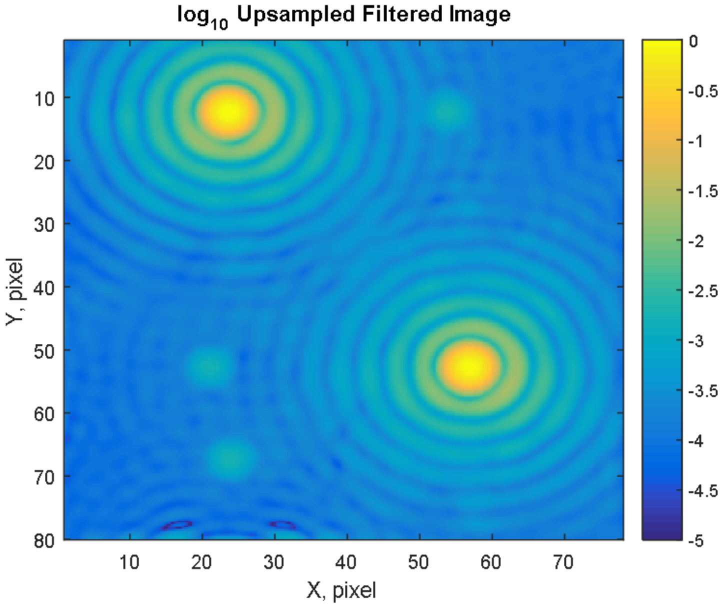
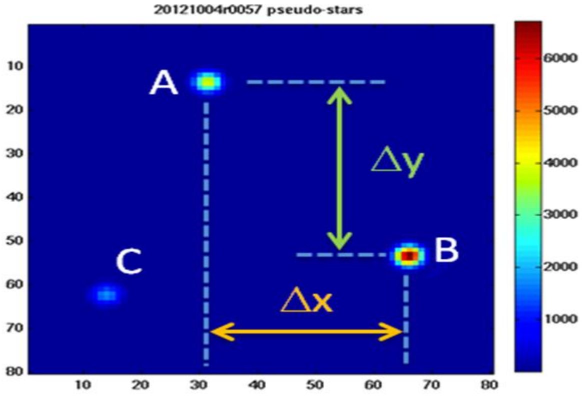
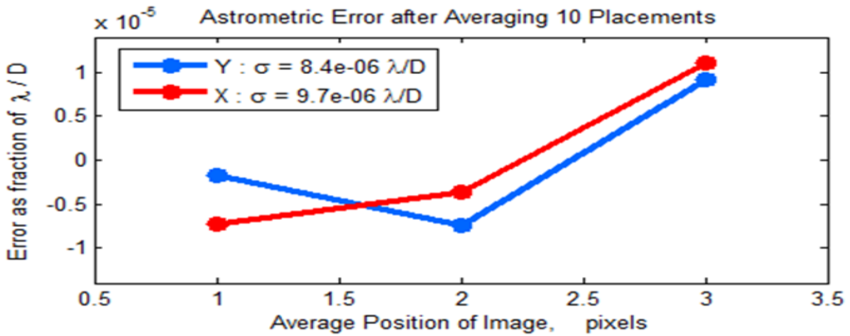
Path to μas Astrometry

M. Shao,





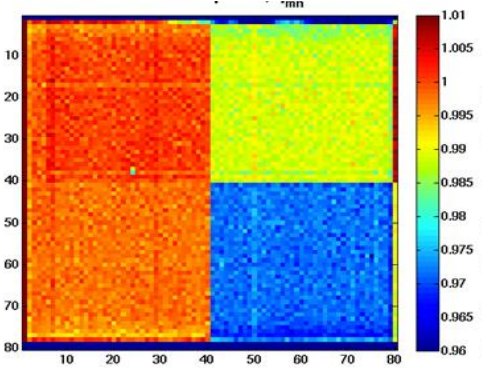


Outline

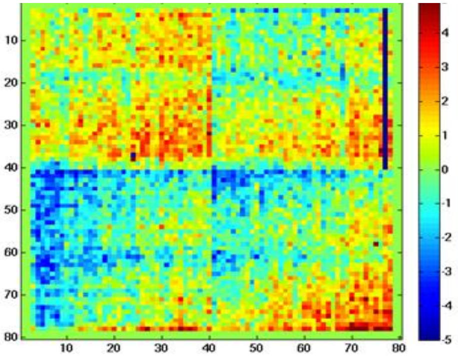
- Error sources in focal plane astrometry
  - Everything that touches a stellar photon can be a source of systematic (instrumental) error
- Telescope
  - Optical distortion
- Detector
  - Pixel geometry and sub-pixel imperfections
    - Most of this talk is on this topic
    - Detector errors unlike “data proc errors” can be fatal. An uncalibrated detector error not only produces errors by them selves, but can corrupt the calibration of optical distortion and other errors.
- Telescope jitter (during a single exposure)
- Data processing
  - Errors can be introduced after the bits are in the computer
  - Imperfect knowledge of PSF, PSF due to pointing jitter, measuring the true PSF on orbit
- MASS (**M**icro**A**rcsecond **S**mall **S**atellite) (35cm telescope, goal ~4 uas astrometry/sqrt(hr))

Pixel Position Errors in CCDs

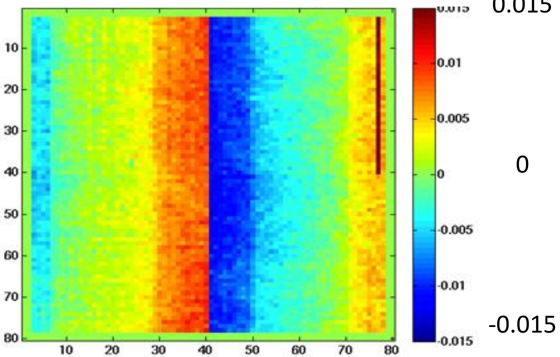
Flat Field Response



Horizontal Pixel Offsets



Vertical Pixel Offsets

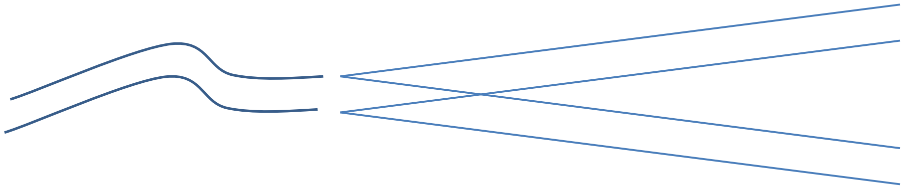


- Detector has four quadrants each with a different flat field response.
- Each half of the detector shows a +/-1.5% pixel skew in the ΔY pixel locations.
  - In the vertical direction there is a 700nm (3% pixel) shift between the left and right halves of the CCD.
- This is a particularly large "systematic" error in the lithographic mask used to manufacture the CCD. Step/repeat errors on many 4K^2 ccd show 100~200nm offsets at the repeat boundaries.
- Besides the large systematic errors, there are "random" pixel position errors that apply to every pixel. These ~70nm rms errors on a CCD with 9um pixels would represent ~0.8% of a pixel

Light Source for Detector Calibration

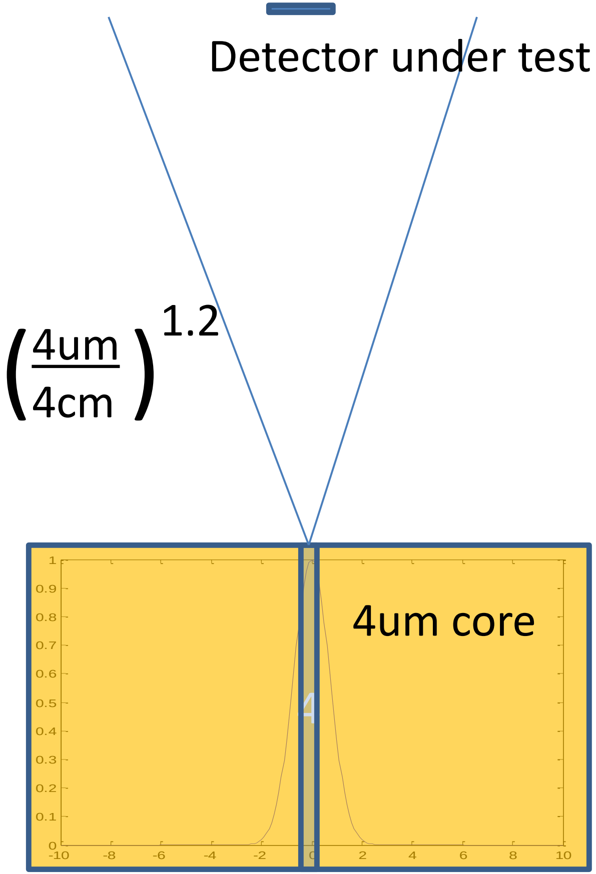
- What are the important properties of the light source for calibrating detectors?
- Dimensional precision (x,y)
- Photometric precision
- What source is closest to perfection?
- Single mode optical fiber.

Wavefront from fiber
Gaussian amplitude
spherical wavefront
from 2 fibers
form fringes



Wavefront from a Single Mode Fiber

- The wavefront from a single mode fiber is the closest thing to a perfect sphere made by Humans.
- Any error is in the flatness of the glass.
- Take 2 inch optic lambda/20 p-v surface. And power spectrum
  - ~ $1/f^{2.5}$
  - On a 4um scale the surface can potentially be flat to ~$10^{-5}\lambda$
- Interference between two spherical wavefronts produce hyperbolic fringes (that visually look like straight fringes)
- The intensity distribution is ideally a gaussian. In reality also very close to a gaussian. Deviations from a gaussian are due to phase to amplitude conversion.



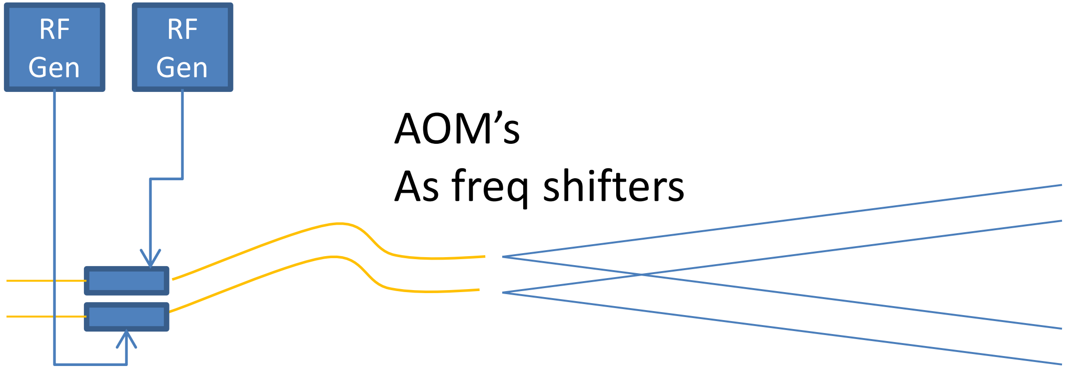
Detector under test

$\left(\frac{4um}{4cm}\right)^{1.2}$

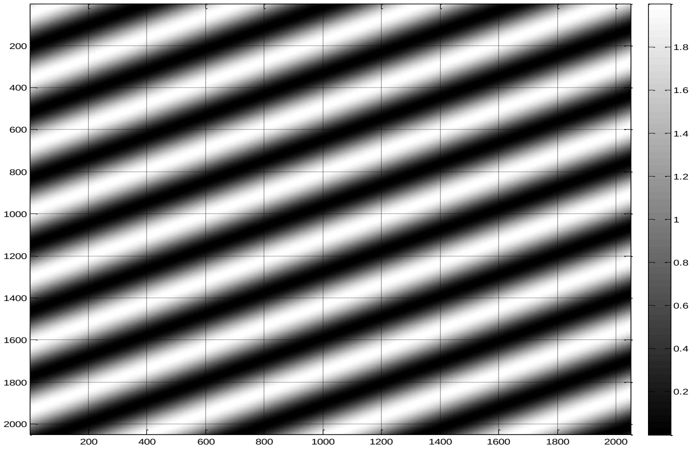
4um core

Fringes from Two Fibers

- There are multiple ways to “move the fringes across the detector”
- One common technique is to use AOM frequency shifters.
  - These devices shift the freq of the laser light by an amount by X hz, the RF signal driving the AOM
  - The accuracy of the freq shift of the laser light is the freq accuracy of the RF source.



AOM’s
As freq shifters

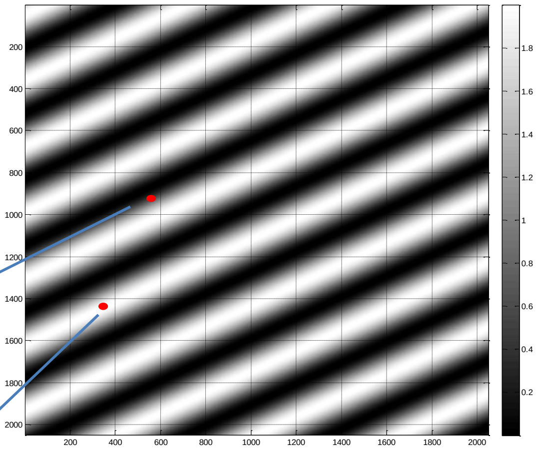


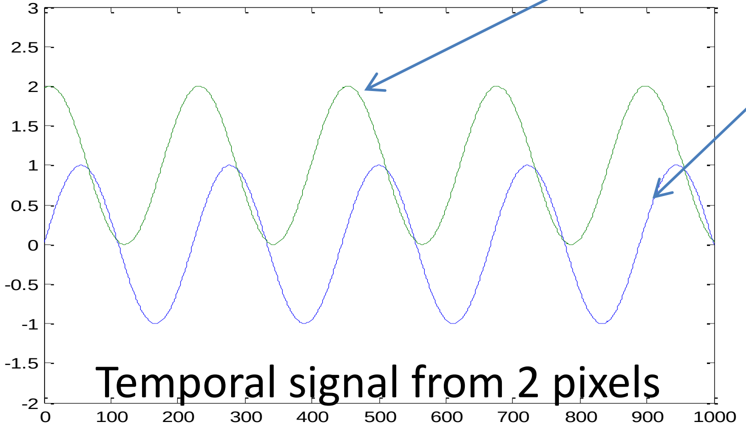
Δf=3.000,000 +/- 1uHz

AOM driven by 2 RF
Sources 40.000,000 Mhz
40.000,003 Mhz

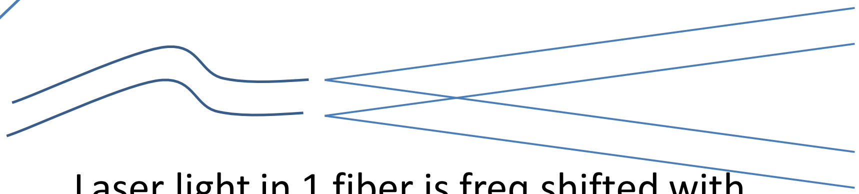
Fringes from 2 Fibers

- The dimensional accuracy of the fringes (across the whole detector) is directly related to the wavefront quality from the fibers.
- The fringes are caused to “move” either with an AOM or stretching the fiber. With an AOM the motion is as linear as the purity of the RF source driving the AOM.



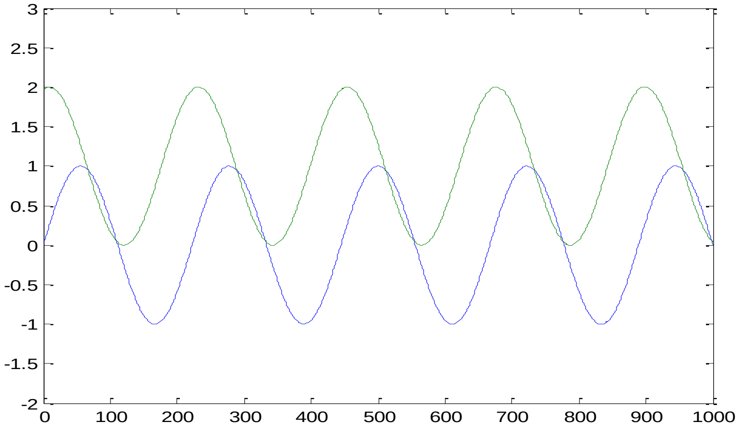


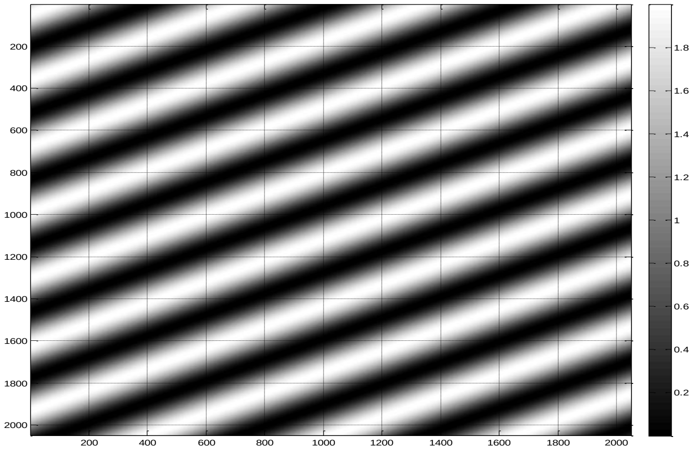
Temporal signal from 2 pixels



Laser light in 1 fiber is freq shifted with respect to the other to provide “moving fringes” ~ a few hz the detector is read out with ~10 reads/λ motion of the fringes

What are We Measuring?





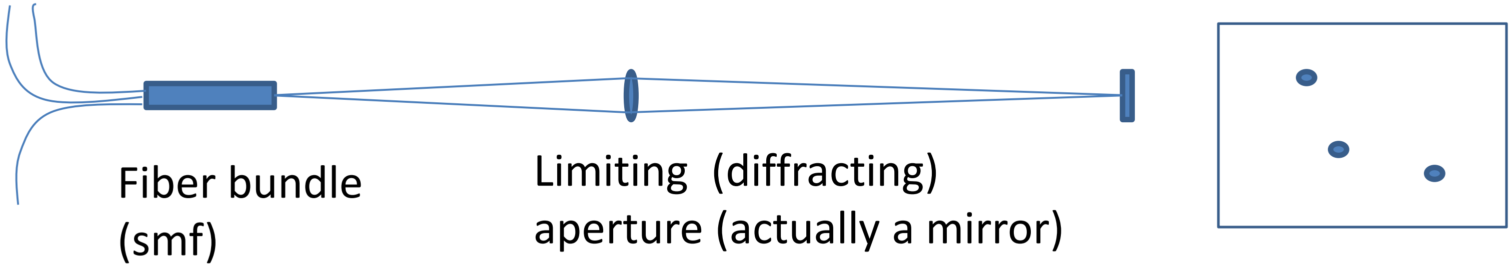
- The fringe is a near perfect sinusoid in space (x,y) and in time (t)
- Flux(i,j,t) = A*Vis*sin(k_x*X+k_y*Y+ ω*t+ϕ)
  - K_x, k_y spatial freq of fringe
  - ω is temporal freq of fringe
  - ϕ is the pixel position in the direction of fringe motion.

The detector only occupies a small part of the Gaussian beam from the fiber

A(i,j) is the sum of the two Gaussians
Vis(i,j) = 2*sqrt(G1*G2)/(G1+G2)

Projecting Point Source PSFs

- A point source diffracts off the focusing optic to produce an airy spot on the detector.

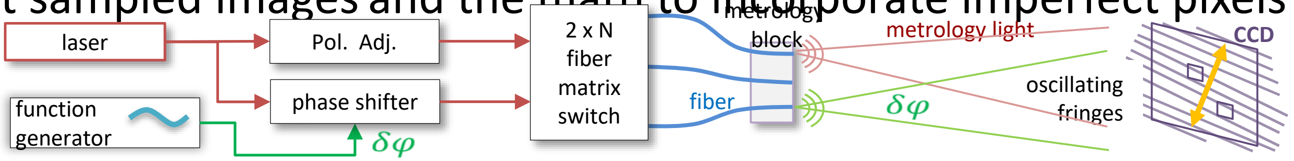


The wavefront from the fiber is near perfect. (geometric point)
There is **only 1 optic** that reimages the fiber to the detector

That optic is not perfect $\lambda/100$, the airy spot is not exactly the bessel function(squared). But since all the images use the same part of the same focusing optic, **all the PSFs are identical**.

Mitigating Focal Plane and Centroiding Errors

- Calibrate the focal plane with **laser metrology**
  - Pixel QE, pixel location, intra-pixel QE(x,y). On orbit only update pixel location (x,y).
- Rather than fit the CCD data to a “reference” PSF, derive the true on orbit PSF with Nyquist sampled images and the math to incorporate imperfect pixels into the fit.



laser

function generator

Pol. Adj.

phase shifter

$\delta\varphi$

2 x N fiber matrix switch

fiber

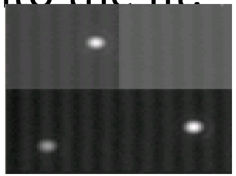
metrology block

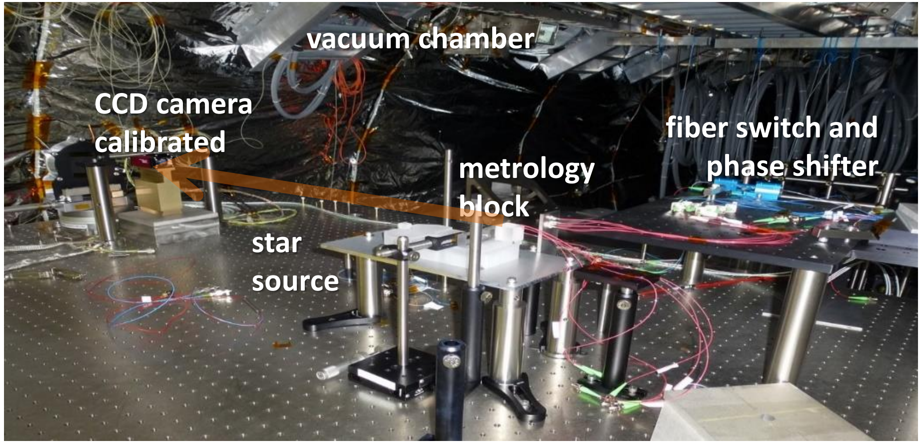
metrology light

$\delta\varphi$

oscillating fringes

CCD





vacuum chamber

CCD camera calibrated

metrology block

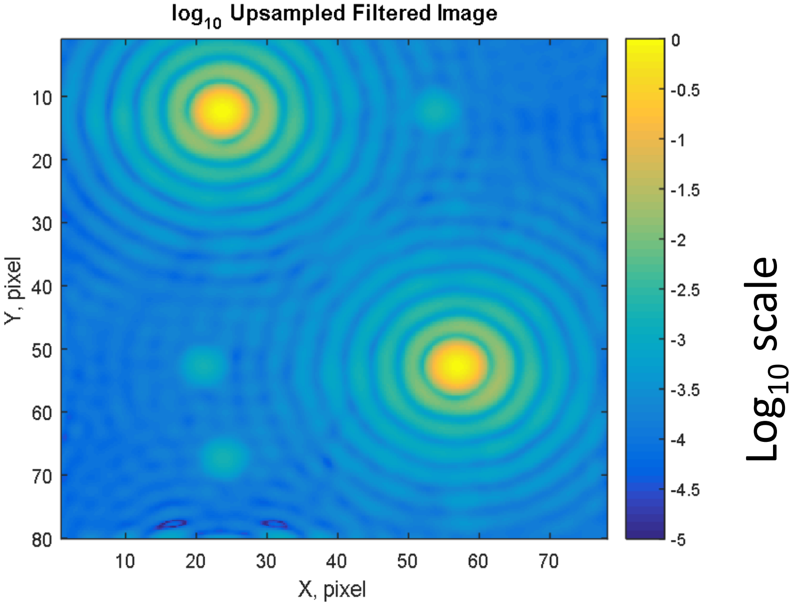
fiber switch and phase shifter

star source

Conceptually, the idea is that with laser calibration of the detector, we’re measuring the position of a star with respect to the laser fringes, not pixel locations.

Image Centroiding to 10^{-5} λ/D

- Images were low pass filtered, and upsampled (to 16pix/(λ/D))
  - Image is taken ~4 pixels/(λ/D)
  - Source is white light ~5% bandwidth
  - Ghost images ~10^{-3} from electrical Xtalk on chip

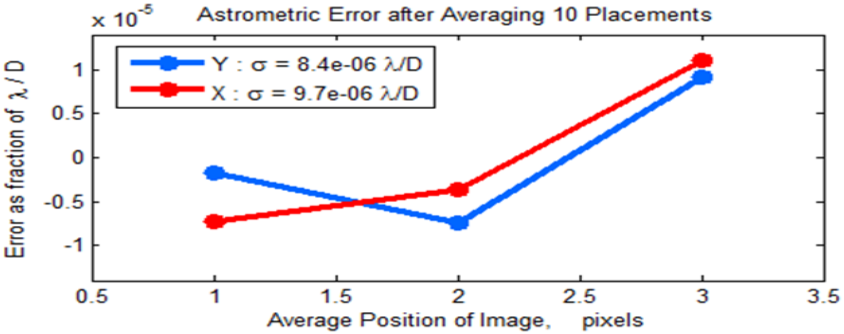


- Very high wavefront quality in test setup. (visually see 8th diffraction ring)
- Parameters fitted
  - X,Y center of image
  - A semi-major axis
  - B semi-minor axis
  - θ angle of semi-major axis
  - DC

Centroiding at 10^{-5} λ/D

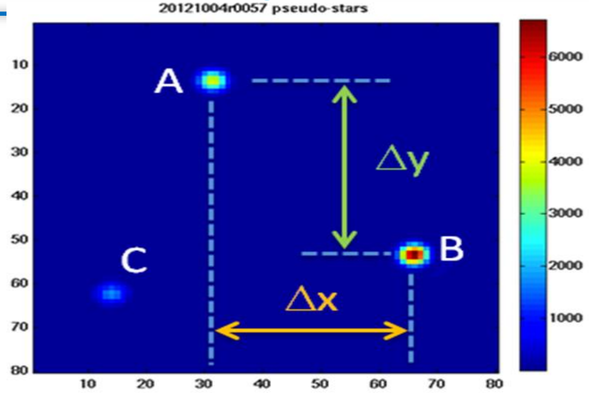
- One of the errors in traditional CCD astrometry is a lack of knowledge of the true optical PSF.
  - But the true optical PSF can be measured with dithered images (applying corrections with subpixel calibration) when the focal plane is not nyquist sampled.

We took the 3 airy spots and move them across 3 pixels of a CCD. Total of 30 positions. The separation between A,B was constant to 1.2e-4 pixels at each of the 10 positions. After averaging 10 positions, the separation agreed to ~10^{-5} λ/D, 4e-5 pixels.



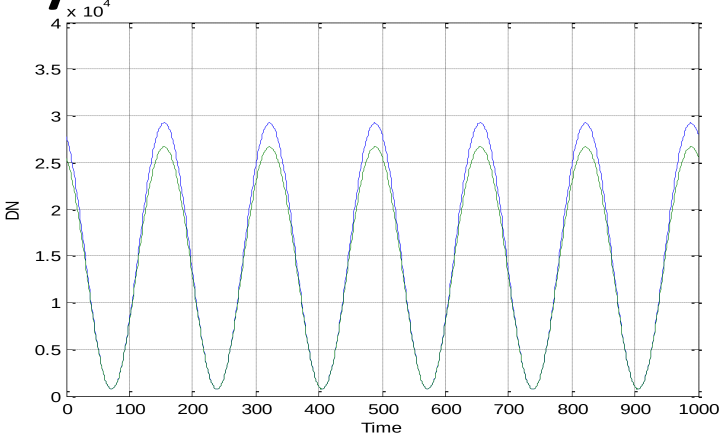
PSF oversampled 4pix/(λ/D)

Achieved average error of 9e-6 λ/D

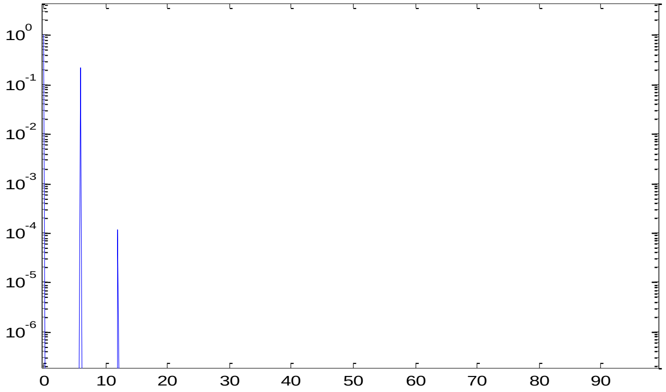


Photometric Linearity Calibration

- For each pixel's output, the laser fringes are a near perfect sinusoid in time. The phase of the sinusoid is as good as the RF generator driving the AOM.
- A deviation of a perfect sinewave is a measure of the non-linearity of the detector.



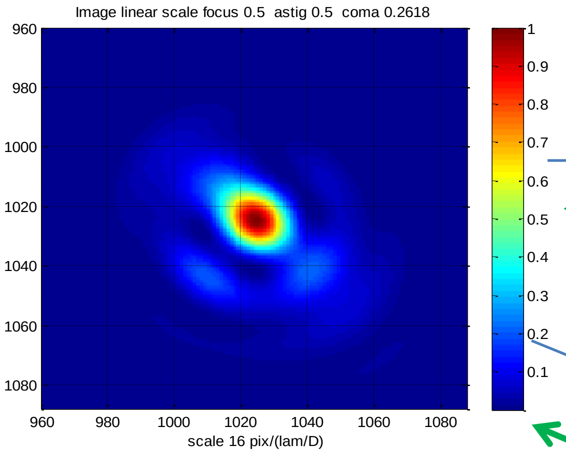
A quick test of photometric nonlinearity is the appearance of a 2^{nd} harmonic. When taking A temporal FFT.



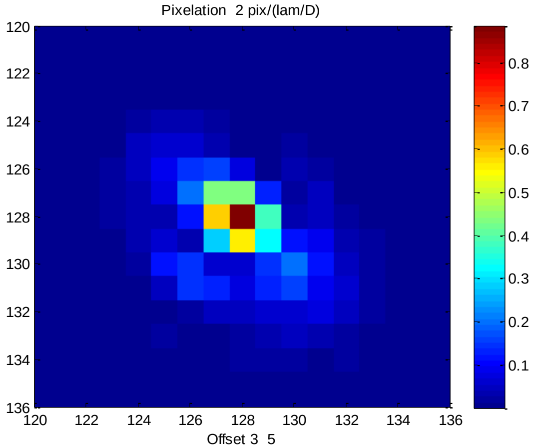
CCDs don't have (much) persistence. But with fiber illumination we can change the temporal freq without affecting the fringe amplitude. A change in amplitude with freq is a sign of persistence.

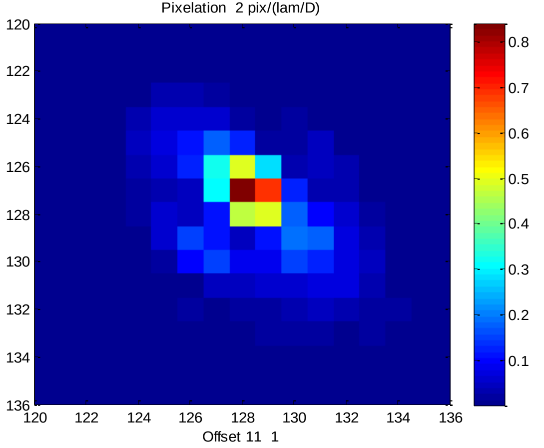
Pixelation Effects

Asymetrical PSF (exaggerated)



Nyquist sampled PSF (with different frac pixel offsets)





Because these images are nyquist sampled any one of these can be used to reconstruct the true optical PSF.

For astrometry, shift the “true” psf until there is a least sq-fit of the pixelated true PSF with the data.

Centroiding, True PSF, Telescope Jitter

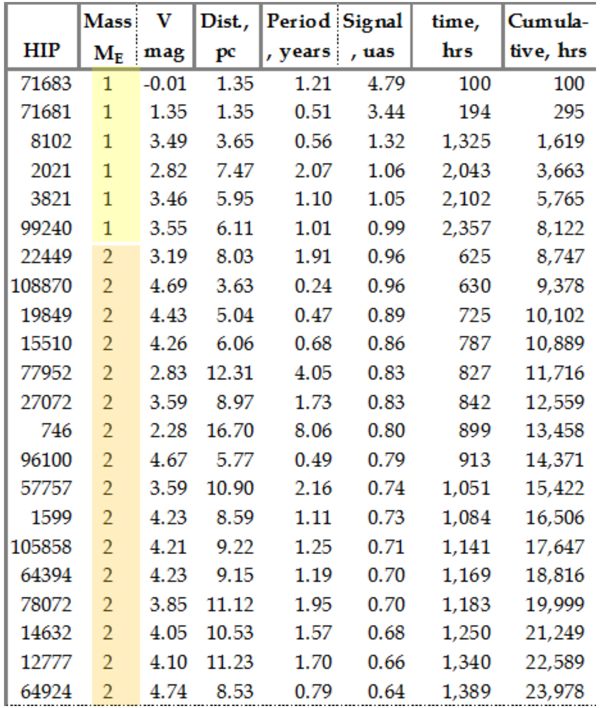
- Normal astrometry/centroiding does a least sq fit of a “model” PSF. (defined analytically, eg Gaussian or diff pattern of the telescope (with correct obscurations)
- The true PSF is not just the FFT of the telescope pupil. The phase errors of the telescope are not captured.
- The true PSF changes before/after launch because of thermal/gravity effects on the telescope are different before/after launch
- The true PSF changes every exposure because the telescope jitter is different every exposure.
- With Nyquist sampling, one has the “true PSF” for every exposure.
- In addition FFT upsampling, one has to account for non-uniform pixel geometry while performing the up sampling.

MASS Study

- NASA astrophysics issued a call for small satellite (ESPA class) astrophysics missions. Larger than cubesat, but smaller than SMEXs. ~45 proposals 9 selected for study.
- Cost cap at $35M for this class of mission
- MASS is a mini-version of NEAT/THEIA
  - **~35cm** telescope
  - Single 100 Mpix CMOS detector focal plane ~0.5deg FOV
  - Weak diff grating for distortion calibration

R~1.7 Re => 5 Me can hold on to a H2 atm
For a billion years (mini-Neptune)

Exo Earth Target List

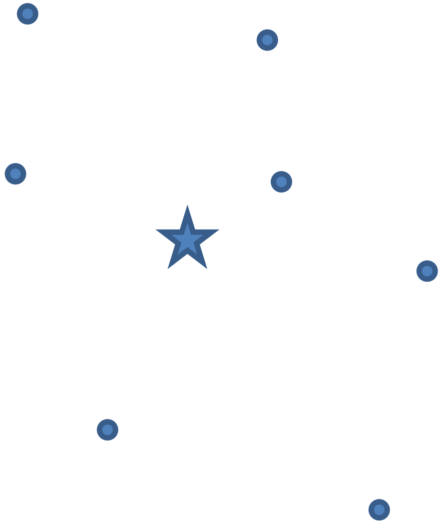


HIP	Mass M_E	V mag	Dist, pc	Period, years	Signal, uas	time, hrs	Cumulative, hrs
71683	1	-0.01	1.35	1.21	4.79	100	100
71681	1	1.35	1.35	0.51	3.44	194	295
8102	1	3.49	3.65	0.56	1.32	1,325	1,619
2021	1	2.82	7.47	2.07	1.06	2,043	3,663
3821	1	3.46	5.95	1.10	1.05	2,102	5,765
99240	1	3.55	6.11	1.01	0.99	2,357	8,122
22449	2	3.19	8.03	1.91	0.96	625	8,747
108870	2	4.69	3.63	0.24	0.96	630	9,378
19849	2	4.43	5.04	0.47	0.89	725	10,102
15510	2	4.26	6.06	0.68	0.86	787	10,889
77952	2	2.83	12.31	4.05	0.83	827	11,716
27072	2	3.59	8.97	1.73	0.83	842	12,559
746	2	2.28	16.70	8.06	0.80	899	13,458
96100	2	4.67	5.77	0.49	0.79	913	14,371
57757	2	3.59	10.90	2.16	0.74	1,051	15,422
1599	2	4.23	8.59	1.11	0.73	1,084	16,506
105858	2	4.21	9.22	1.25	0.71	1,141	17,647
64394	2	4.23	9.15	1.19	0.70	1,169	18,816
78072	2	3.85	11.12	1.95	0.70	1,183	19,999
14632	2	4.05	10.53	1.57	0.68	1,250	21,249
12777	2	4.10	11.23	1.70	0.66	1,340	22,589
64924	2	4.74	8.53	0.79	0.64	1,389	23,978

R~1.26 Re => 2 Mearth

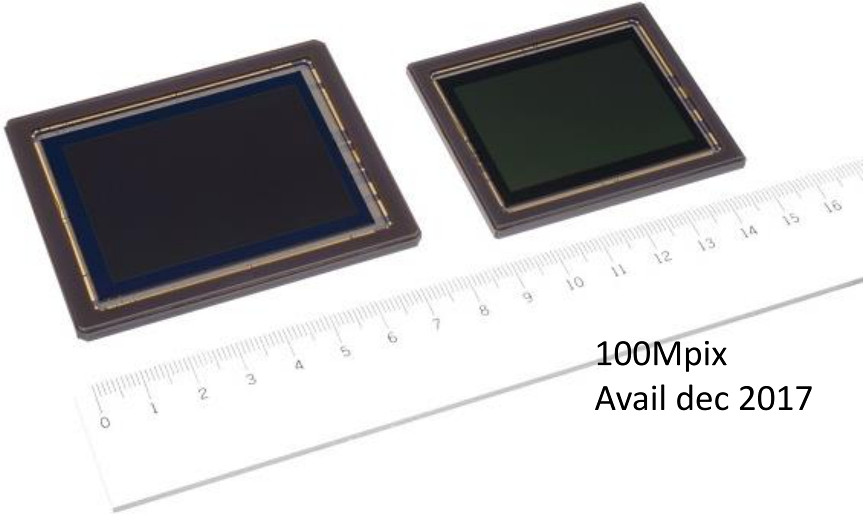
MASS Description 2

- Like NEAT/THEIA (ESA proposals) MASS measures the motion of a target relative to reference stars
- Photon limited by ref stars (not target star) need ½ degrees for ~100 (10~15) mag ref stars
- ~4uas/sqrt(hr) photon limit of ref stars
- Can find exo-Earths around single and binaries.
- For binaries, know which star the planet is orbiting (no ambiguity)



Large Format Detectors Now Available

- Large format 65~150 Mpix detectors are now available.
- Focal plane sensors from Sony, E2V, Gpixel have recently been introduced with the key properties suitable for precision astrometry
- Backside (no lenslets)
  - Subpixel calibration is possible
  - Higher QE
- Low read noise, fast frame rates.
  - Enable use with less stable spacecraft.
- Large format $(0.52\ \text{deg})^2$ with nyquist sampling 0.19 arcsec/pix



100Mpix
Avail dec 2017

Sony 100Mpix and 150 Mpix cmos
Sensors, backside, < 2e read noise
2~3 frames/sec.

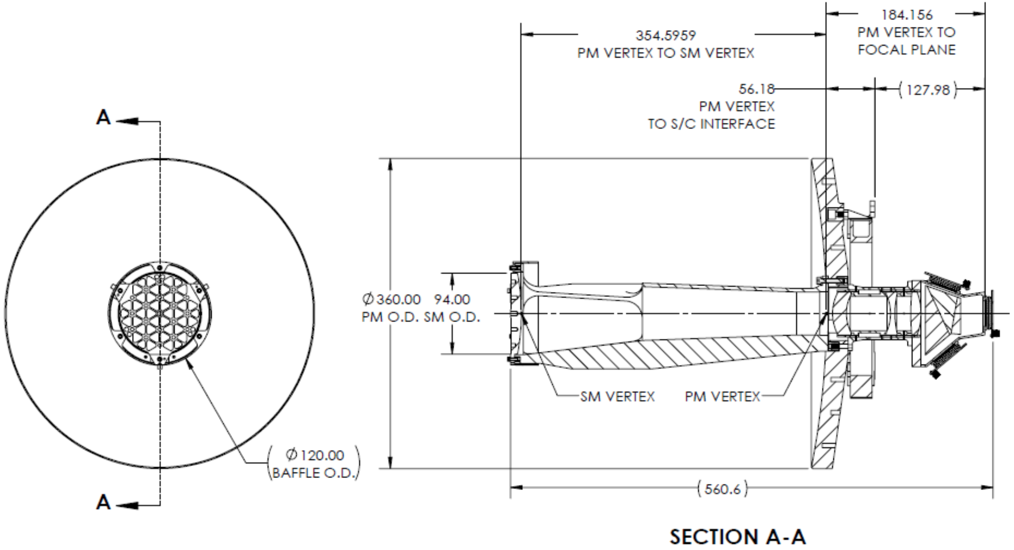
MASS (Small Sat study)

4uas in 1 hr
1 Mearth – 1AU planet around
6 stars, 2Mearth ~16 stars

Detector calibrated on the ground.

~100 postage stamps for ~100 reference stars 10~16mag

Equiv # pixels for diff pattern of the target star



COTS SiC telescope 33cm dia
With Sony 100 Mpix sensor (lab calibration)
Weak diff pupil (dot pattern) for Distortion cal.

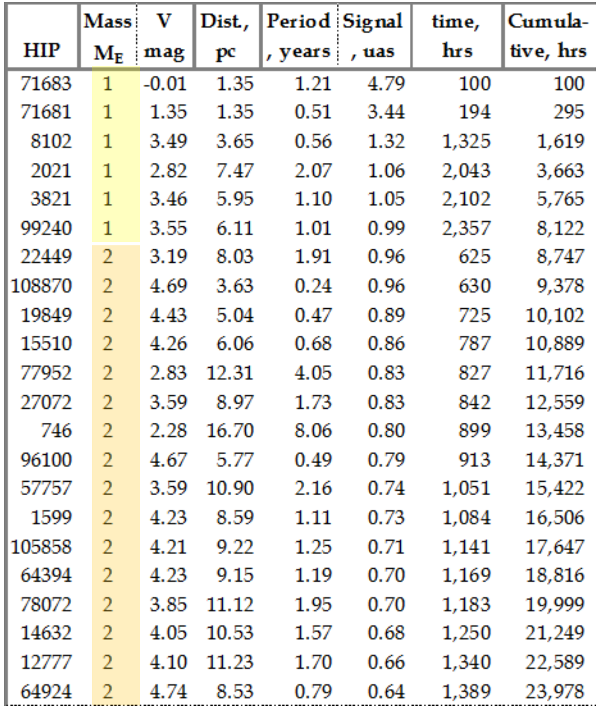
Nearby Exo-Earths

- Search to 1Mearth (6), 1Me(16) planets
- How wide in the HZ? (0.7~1.4AU) **BUT** the range of liquid H2O is large for different types of ExoEarths. BUT for our Earth, liquid H2O is 0.9~1.15 AU.

If every star has a 1 Mearth planet between 0.7~1.4AU ~ 30% of them will have liquid water.

- Astrometry wrt ref stars is 2D astrometry. (3D orbit)
- If the goal is to eventually get direct detection + astrometry, you can't ignore single stars.

Exo Earth Target List



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