High Precision Focal Plane Astrometry
… and possibilities for the HDST

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* Presenting

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Overview

- The calibration techniques we are developing for WFIRST can be also used on HDST, turning it into a revolutionary astrometric instrument
- Estimated astrometric accuracy is 10’s of nano arcseconds

- Two examples of what such a capability allows us to do
  - Parallaxes of galactic neighborhood out to 100 Mpc
  - Astrometric characterization of sun like stars out to 50 pc
      - Masses, orbit parameters, inclinations
    - **Broad search for true exo-Earths** around sun like stars
      - Thousands of stars can be searched with a one year allocation
    - **Precision targeted investigations** of RV and Transit objects of interest
      - Modest demand: e.g. for a target 30 pc away , 100 observations *totaling* < 6 hrs

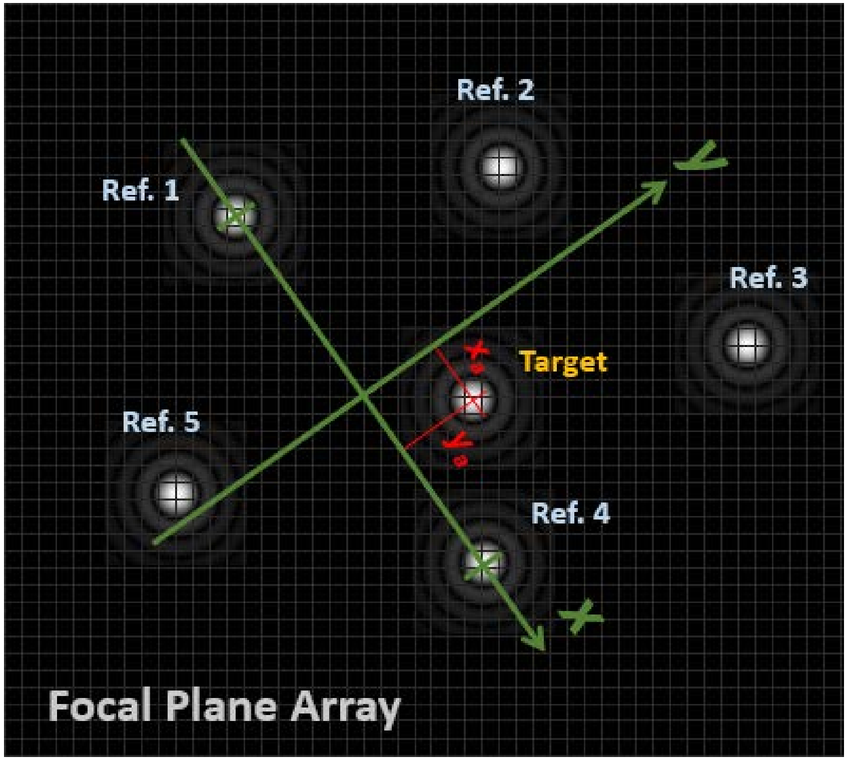
Focal Plane Astrometry

- Focal Plane Astrometry is in principle simple:
  - Distances between stellar images is directly related to angular distances on the sky
- The most important sources of error are:

  1. Photon noise
  2. Astrophysical noise (sun spots)
  3. Focal Plane imperfections

  ★ 4. Optical System field distortions

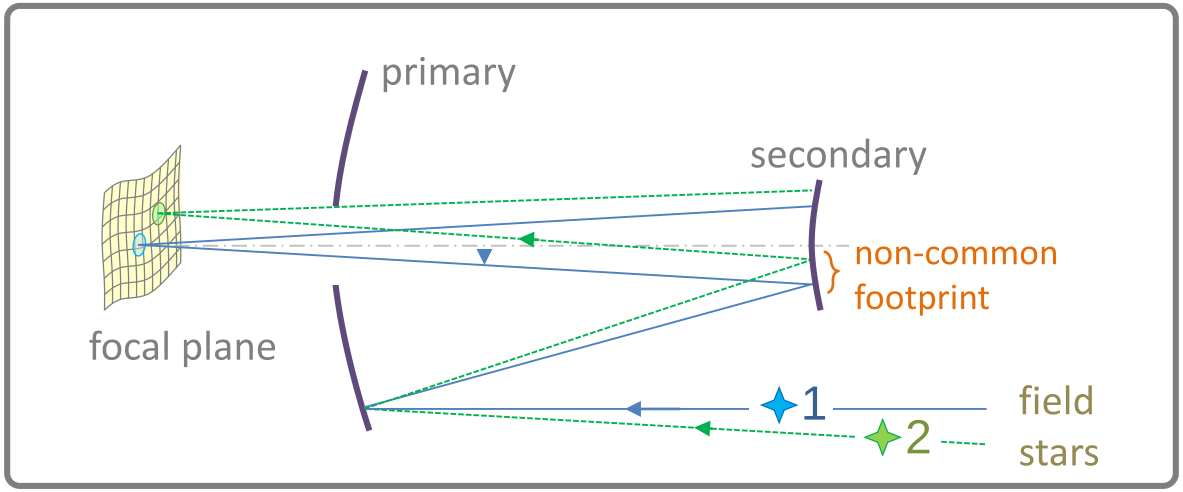
  5. Image position estimation



★ : What we are addressing here

The Dominant Systematic Errors

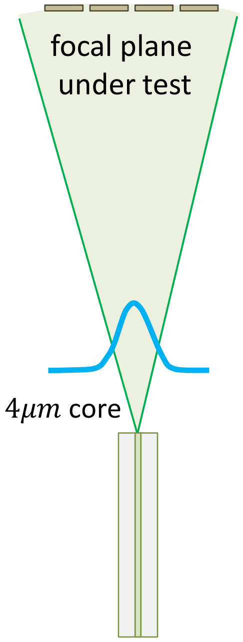
- There are three categories of errors that have to be calibrated to enable μas astrometry telescopes
  1. **Focal plane imperfections (detector errors)**
     - Pixels are not on a perfect regular grid
     - Their QE's are different and not necessarily flat within a pixel
  2. **Non-common footprints and field distortions (optical errors)**
     - light from different stars in the field falls on different parts of the focal plane
     - wavefront errors coupled with non-common footprints give rise to field distortions
  3. **Image position estimation errors (algorithms)**
     - Centroiding algorithms that assume a PSF can have systematic errors when the assumed PSF is not the same as the true PSF.



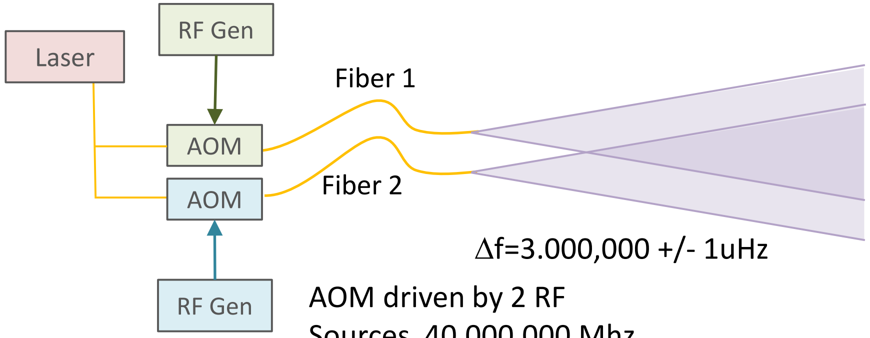
On a TMA telescope, largest beamwalk occurs on the tertiary mirror.

The Yard Stick: Fringes from Two Fibers

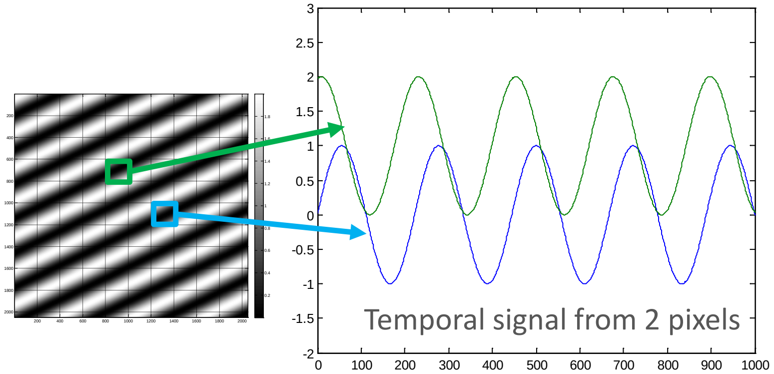
- The wavefront from a single mode fiber is the closest thing to a perfect sphere made by Humans.
  - Any error is in the flatness of the glass
  - A 2 inch optic can be polished to $\lambda/20$ p-v surface
  - Assuming a surface error power spectrum that goes as $f^{-2.5}$, on a 4 um scale the surface can potentially be flat to $\sim 10^{-5}\ \lambda$
  - The intensity distribution is a Gaussian
- Interference between two spherical wavefronts produces hyperbolic fringes (approximately straight)



AOM's
As frequency shifters



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



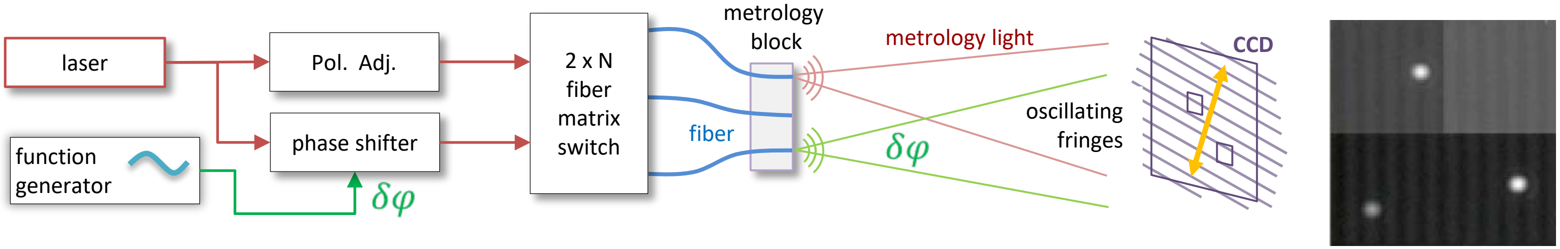
Temporal signal from 2 pixels

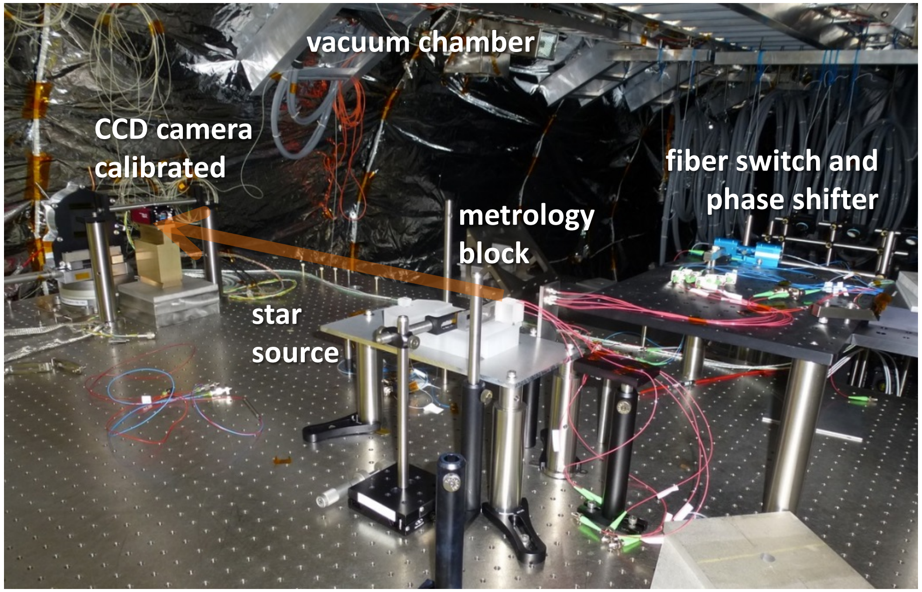
Δf=3.000,000 +/- 1uHz

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

Detector Calibration Testbed

- 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.



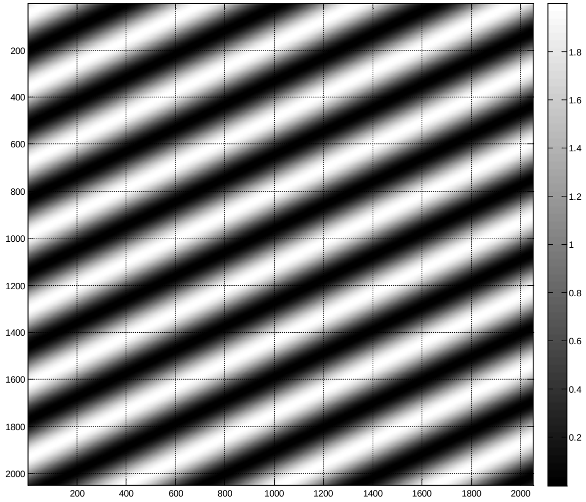


Conceptually, the idea is that with laser calibration of the detector, we’re measuring the position of a star with respect to the laser fringes, not pixel locations.

All components of the metrology system are common components used in fiber optic communications. Many, perhaps all are flight qualified. All components are either totally passive (e.g. fiber) or have very high mechanical resonances (shock insensitive) and are radiation insensitive.

Measuring Intra-pixel QE variations

- The fringe pattern from interfering light from two optical fibers is a sine wave.
- The recorded image is the product of the sine wave with the QE of the detector.
- We're measuring the OTF of every pixel in detector.

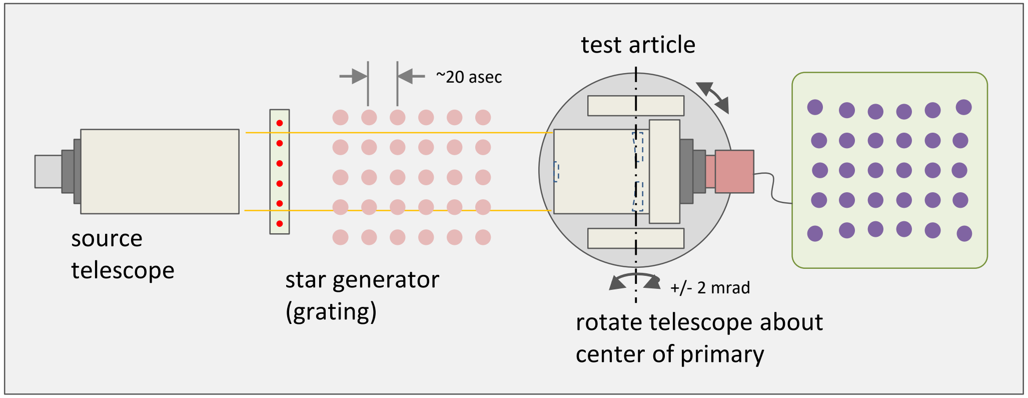


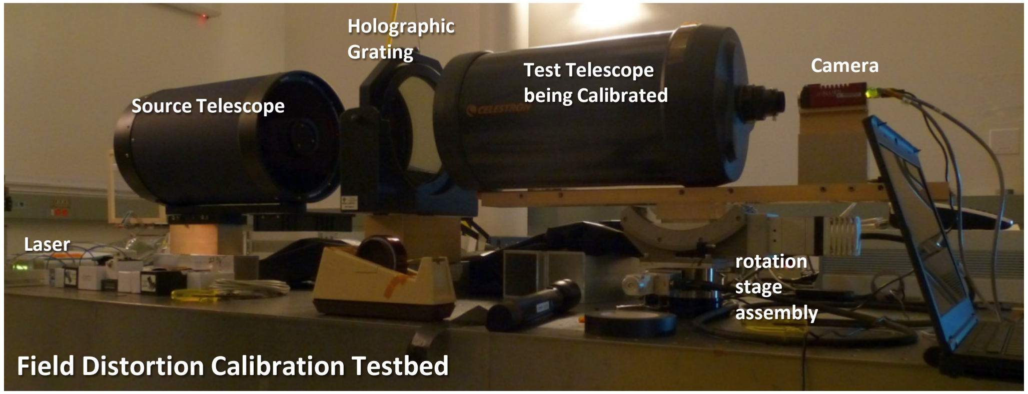
Current setup has 7 fibers, (used 2 at a time) 21 different baselines in different orientations and fringe spacings.

Laser fringe calibration advantages
All pixels are calibrated at the same time
Fringe geometry accurate across the whole focal plane
(pixel spacing accurate 1e-9)

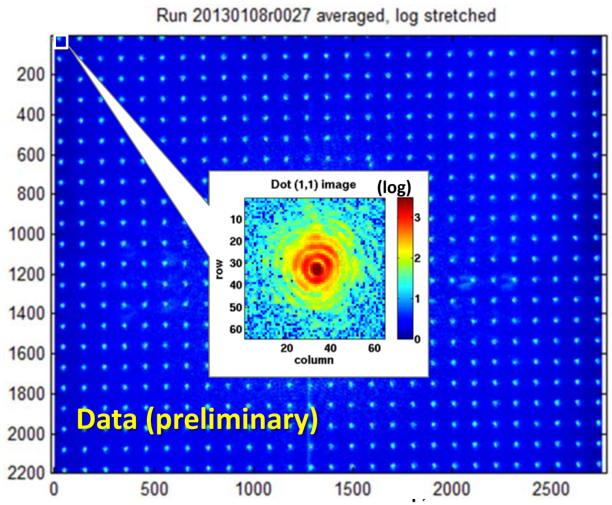
Calibrating Field Distortion

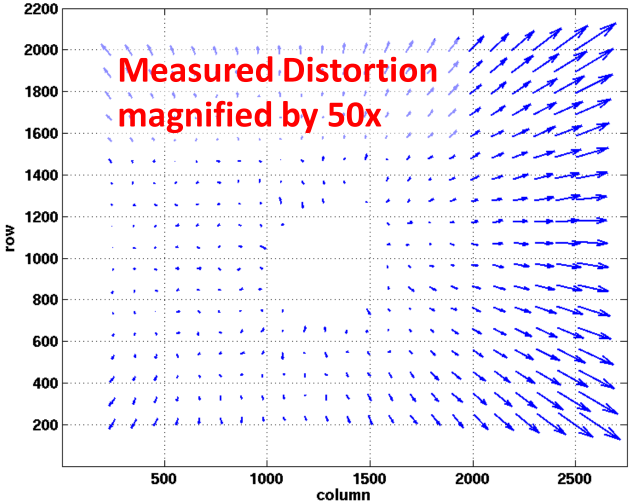
- Diffractive grating generates a field of stars (Guyon Technique)
  - In lab via grating; on NRO via dots on primary
- Measure field distortion from dot location gradients





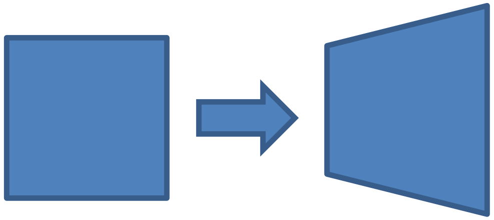
Field Distortion Calibration Testbed





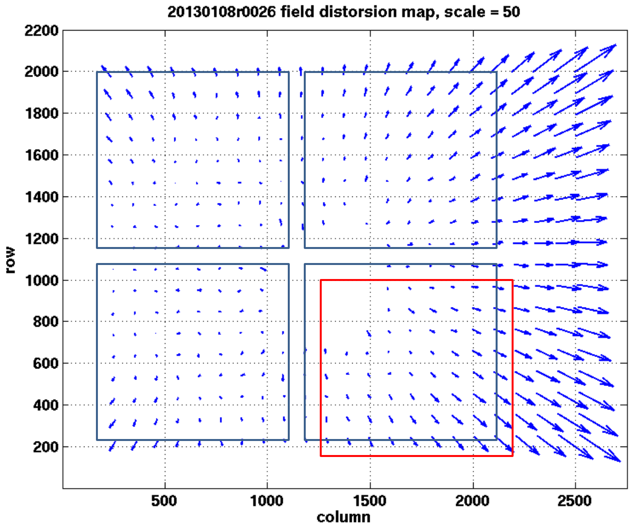
Mosaic Motion and Field Distortion

- GAIA will provide positions for ~50 million stars with ~10 uas accuracy.
  - (and ~1e9 stars to ~100uas)
- Several different types of focal plane change



Chip distortion 40mm chip *1e-5CTE*0.01K
~ 4nm expansion of 1 chip ~40 uas
Thermal gradients within a chip will produce more complex geometric distortion of the pixel location. Metrology would measure position of **every pixel** to 0.1nm.

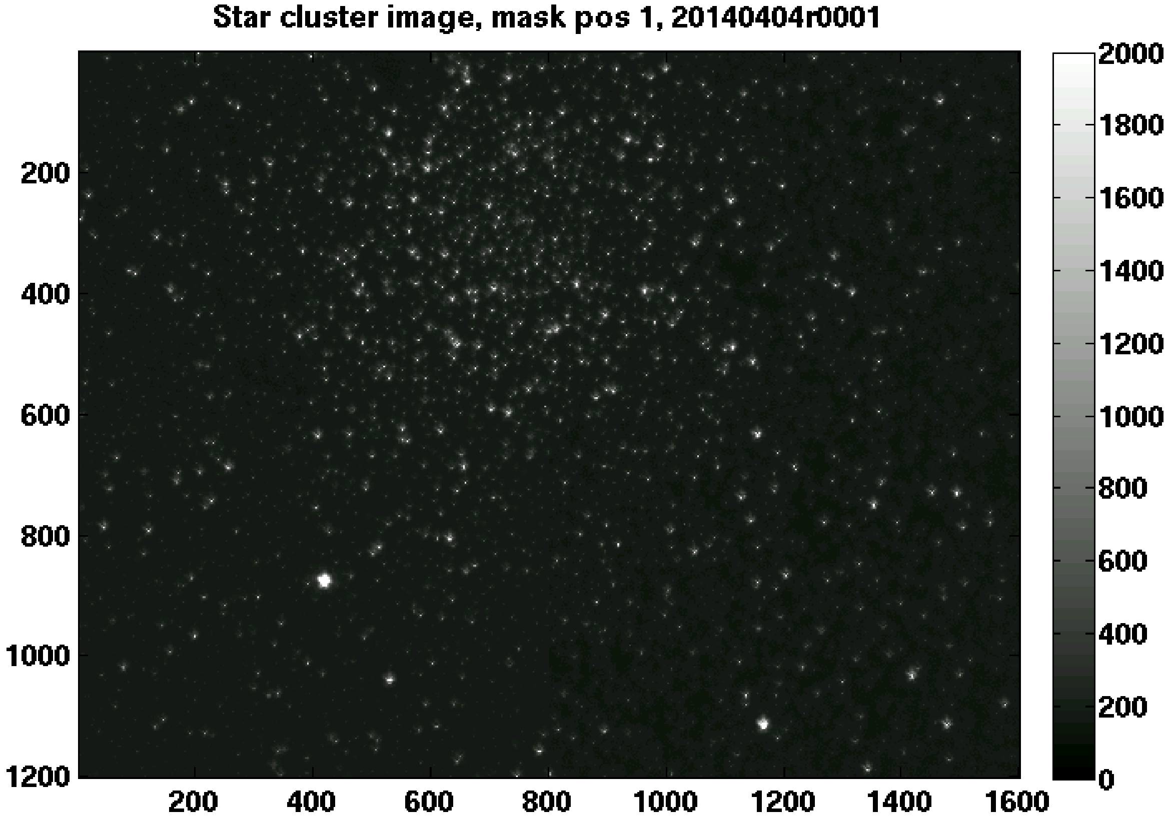
Mosaic distortion. Relative motion
Between detectors in focal plane
Couples to optical distortion



Field distortion stable to
< 1 uas for ~ 1 day
consistent with Coronagraph req

If chip distortion and mosiac distortion are arbitrarily complex, it can not be separated from optical distortion. But if chip/mosiac distortion can be modeled with N parameters << #GAIA stars in the field, it may be separable. But metrology of the focal plane greatly simplifies distortion calibration

Field Distortion Calibration (Traditional Approach)



We had MDL make a mask, representative of a globular cluster 47 Tuc.

~20,000 stars over ½ deg.

Move the star field ~20% of the FOV to ~5 positions.

Model field distortion as a polynomial (or other basis function) and solve for the model coef.

Fortunately, WFIRST AFTA telescope optics will be very stable (to meet coronagraph requirements) distortion calibration repeated every few days/weeks.

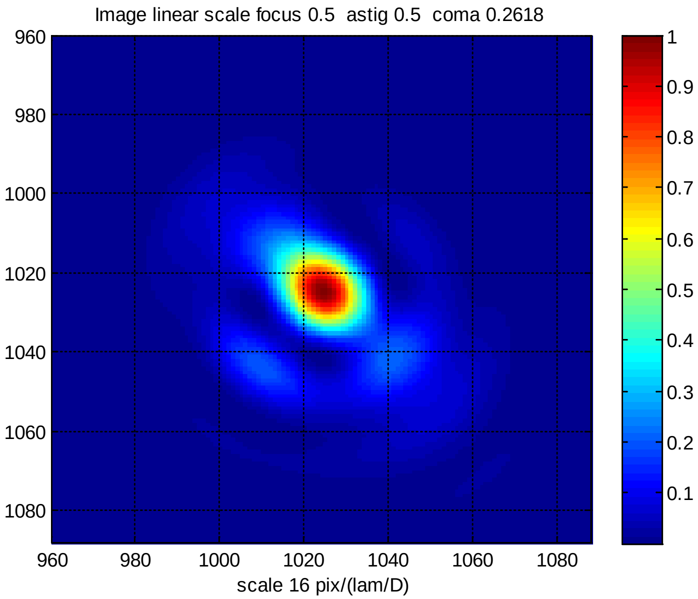
PSF Modeling and Nyquist Sampling

- Simple centroid estimators $(A-B)/(A+B)$ (quad cell centroid) and center of gravity centroid estimators $\sum i \cdot I(i)/\sum I(i)$ are not used for precision astrometry. (such as on HST)

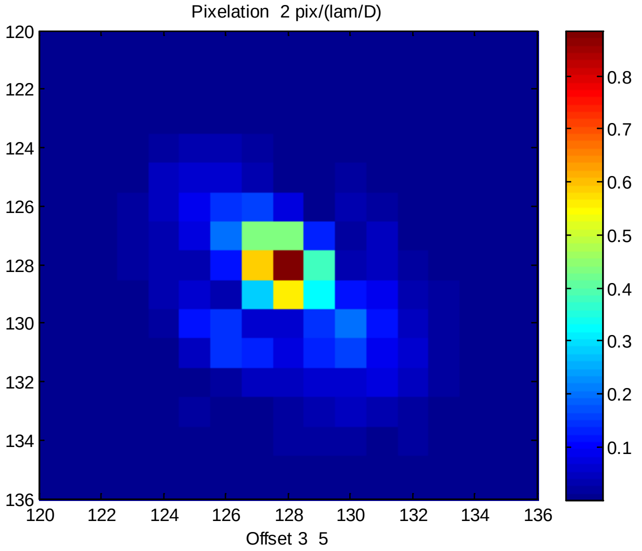
- The normal approach is to perform a least squares fit of a pixelated model to the data. The model PSF (often an analytical model) is shifted in X, Y and intensity until the data and the model have the smallest different (Least sq)
  - Problems:
    - The PSF depends on the wave front errors caused by imperfect optics.
    - The PSF changes across the FOV.
    - The PSF depends on the color of the star.

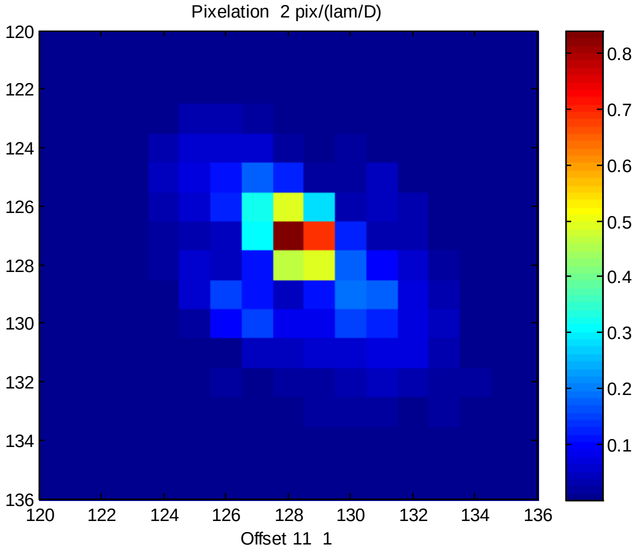
Sampling Theorem Guarantees complete representation of Nyquist-sampled PSF

Asymetrical PSF (exaggerated)



Nyquist sampled PSF at two different offsets)





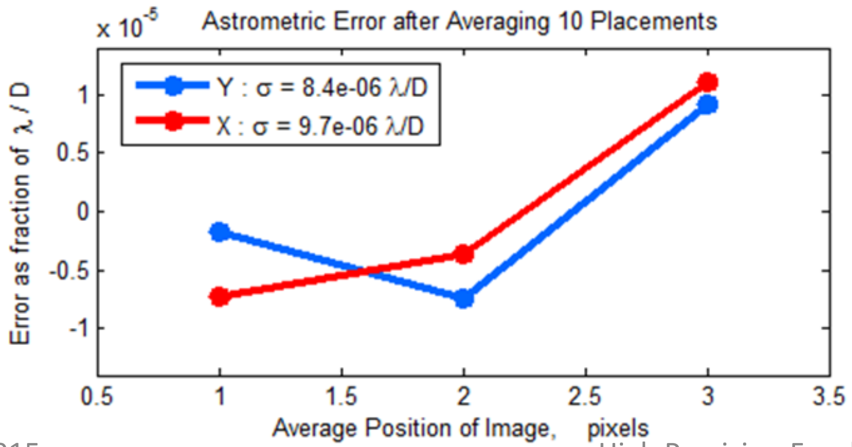
Because these images are Nyquist sampled any one of these can be used to reconstruct the true optical PSF.

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

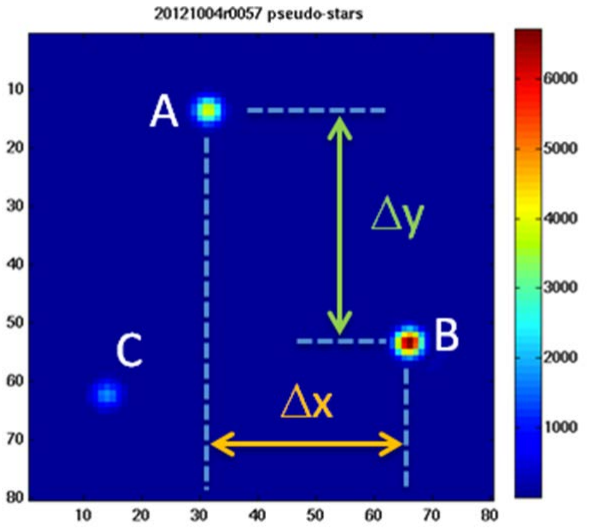
Demonstrating Astrometry at 4e-5 pixel

- Combination of focal plane calibration and improved PSF position estimation is used for a complete astrometry demonstration
  - 3 airy spots were moved them across 3 pixels of a calibrated CCD
  - Total of 30 positions, sub-averaged into 3 groups of 10
  - 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.

Achieved average error of 9e-6 λ/D

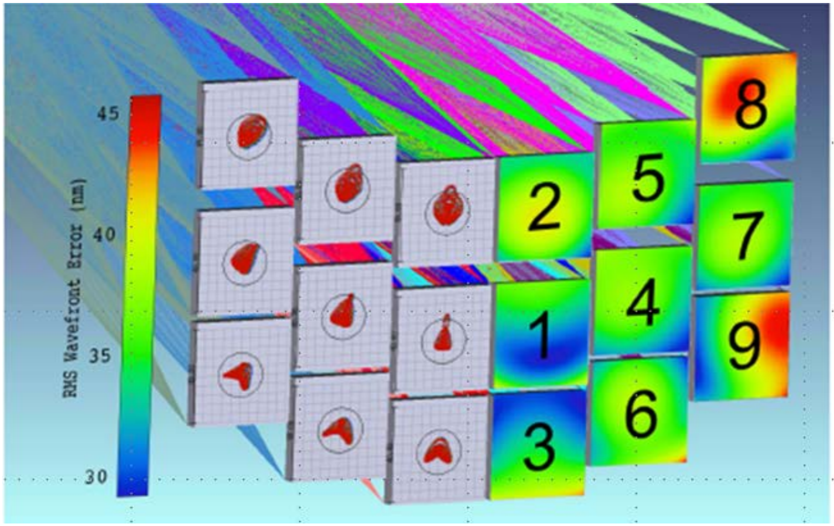


PSF oversampled 4pix/(λ/D)



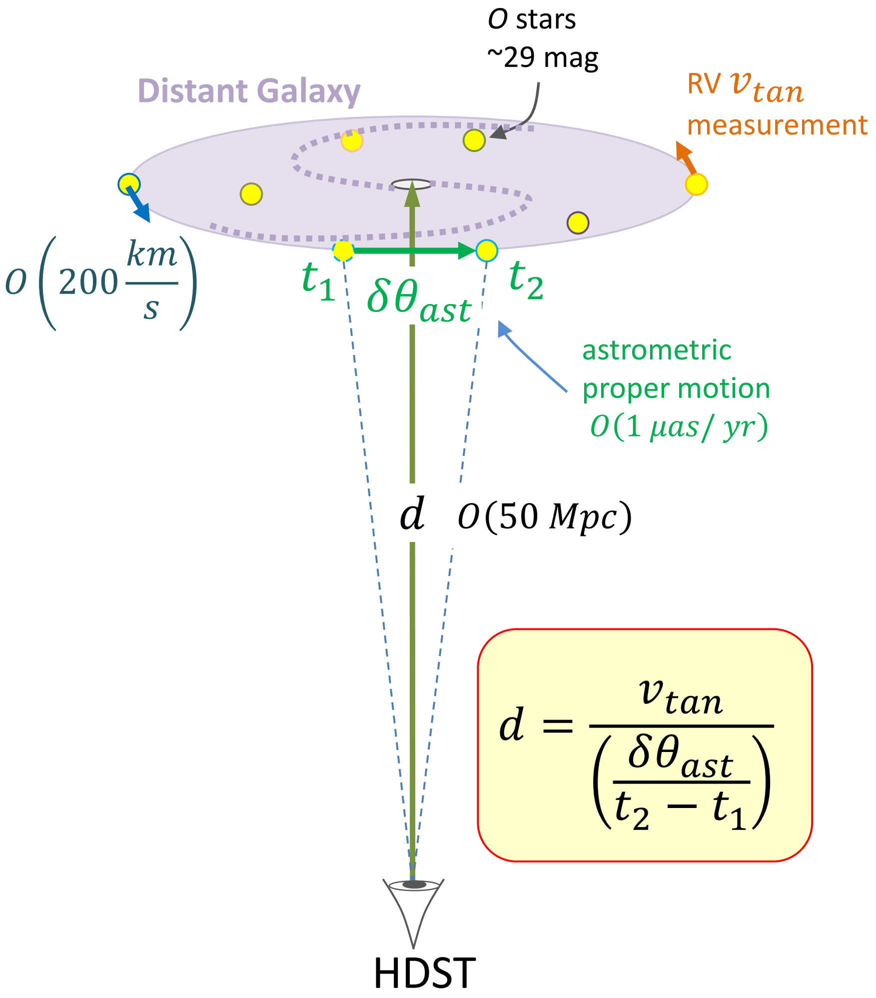
Calibration Benefits to WFIRST

- Astrometry at ~ 1~10uas
- photometry at 10-4~10-5. (can't do astrometry at 1e-5 pix without photometry)
  - This is Kepler level photometry (if photon statistics allow)
- Correction of asymmetrical PSFs in images of Galaxies for Weak Lensing
- If the spatially varying PSF also changes in time (over weeks/months) that can be tracked as well.



Dynamical Parallaxes of Galaxies

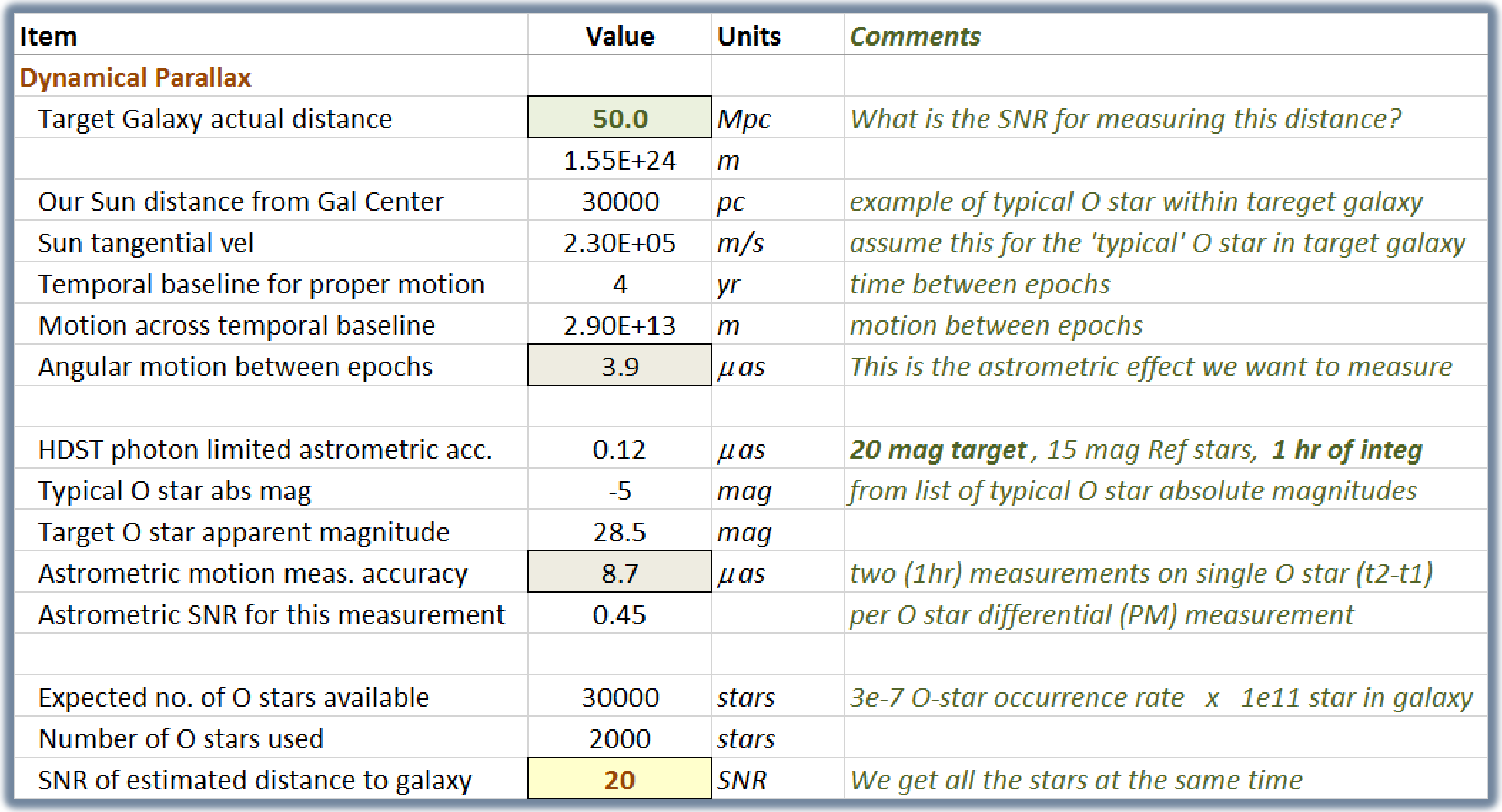
- HDST can obtain distances to nearby galaxies using *Dynamic Parallax:*
  - Choose bright, *O* stars in another galaxy
  - Measure proper motion through astrometry
  - Measure tangential velocity
    - Radial velocity
    - Oblateness of galaxy
  - Average over > 2000 *O* stars within the distant galaxy
    - all target stars simultaneously in each epoch
- HDST's large aperture enables high precision astrometric measurements of extreme faint objects



$$d = \frac{v_{tan}}{\left(\frac{\delta\theta_{ast}}{t_2 - t_1}\right)}$$

Estimated SNR for 50 Mpc distant galaxy

- Expect thousands of *O*-stars in one galaxy; assume 2000 tracked

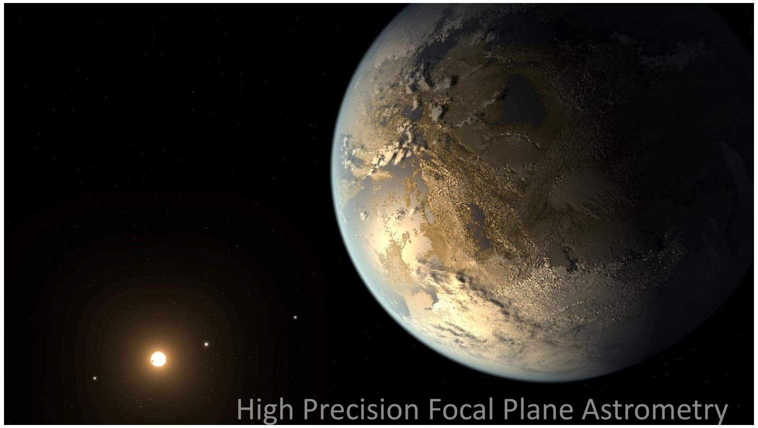


Item	**Value**	**Units**	***Comments***
Dynamical Parallax			
Target Galaxy actual distance	**50.0**	*Mpc*	*What is the SNR for measuring this distance?*
	1.55E+24	*m*	
Our Sun distance from Gal Center	30000	*pc*	*example of typical O star within tareget galaxy*
Sun tangential vel	2.30E+05	*m/s*	*assume this for the 'typical' O star in target galaxy*
Temporal baseline for proper motion	4	*yr*	*time between epochs*
Motion across temporal baseline	2.90E+13	*m*	*motion between epochs*
Angular motion between epochs	3.9	*µas*	*This is the astrometric effect we want to measure*
HDST photon limited astrometric acc.	0.12	*µas*	***20 mag target**, 15 mag Ref stars, **1 hr of integ***
Typical O star abs mag	-5	*mag*	*from list of typical O star absolute magnitudes*
Target O star apparent magnitude	28.5	*mag*	
Astrometric motion meas. accuracy	8.7	*µas*	*two (1hr) measurements on single O star (t2-t1)*
Astrometric SNR for this measurement	0.45		*per O star differential (PM) measurement*
Expected no. of O stars available	30000	*stars*	*3e-7 O-star occurrence rate x 1e11 star in galaxy*
Number of O stars used	2000	*stars*	
SNR of estimated distance to galaxy	**20**	*SNR*	*We get all the stars at the same time*

On a galaxy 50 Mpc out, photon noise limit is ~ 5% distance measurement with 2 hrs of integration over 2 epochs 4 years apart

Exo-Earth Detection with HDST

- The large collecting aperture of the HDST makes astrometry at tens of *nano* arcseconds possible
- True Exo-Earths are terrestrial Earth mass planets in the habitable zones of stable, luminous, sun-like stars
  - G stars like the sun are preferred targets for true Exo-Earths
    - The sun is among the 10% most massive stars in the Milky Way
  - A more comprehensive search would encompass all FGK stars
- HDST allows search of true exo-Earths on a grand scale
  - Thousands of F, G, K stars with sensitivity down to 1 Earth at 1 AU



Broad Exo-Earth Search with HDST

Astrometric precision, photon noise (nas)

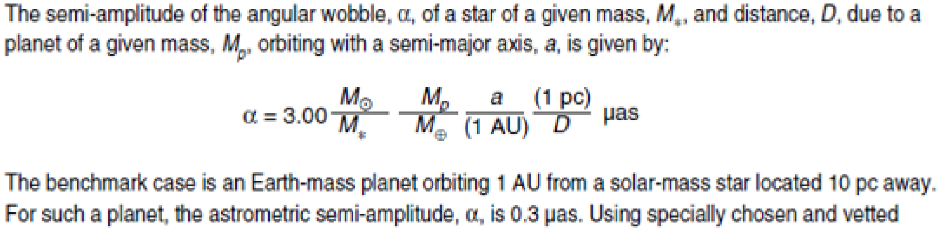
No. of G stars [1]	No. of FGK stars	Distance pc	Astrom. sign. [2] (nas)	Tinteg(sec) / observ 122.539	photon noise (nas) 7	star spot noise nas	Tot. Astr. Error (nas)	Nobs per target	Integr. time (hrs) tot/target	FGK Tinteg days	FGK Days Cum	FGK Stars Cum	G Tinteg days	G Days Cum	G Stars Cum
20	70	10	300	100	90	250	266	27	0.8	4	4	70	1.3	1.3	20
43	164	15	200	100	90	167	189	31	0.9	12	16	234	3	4	63
85	322	20	150	100	90	125	154	36	1.0	27	43	556	7	11	148
140	532	25	120	100	90	100	134	43	1.2	53	96	1088	14	25	288
209	794	30	100	200	63	83	105	37	2.1	102	198	1882	27	52	497
292	1109	35	86	200	63	71	95	42	2.3	162	360	2991	43	95	789
388	1477	40	75	200	63	63	89	48	2.7	246	606	4468	65	159	1177
499	1897	45	67	300	52	56	76	44	4	386	992	6365	102	261	1676
623	2369	50	60	300	52	50	72	49	4	537	1530	8734	141	402	2299
761	2894	55	55	300	52	45	69	54	5	724	2253	11628	190	593	3060
913	3472	60	50	400	45	42	61	51	6	1025	3278	15100	269	862	3973
1078	4102	65	46	400	45	38	59	56	6	1329	4607	19202	349	1211	5051
1258	4784	70	43	500	40	36	54	53	7	1761	6368	23986	463	1675	6309
1451	5519	75	40	500	40	33	52	58	8	2223	8591	29505	584	2259	7760
1658	6307	80	38	500	40	31	51	62	9	2716	11306	35812	714	2973	9418
1878	7147	85	35	600	37	29	47	60	10	3474	14781	42959	913	3886	11296
2113	8039	90	33	600	37	28	46	64	11	4168	18949	50998	1096	4981	13409
2361	8984	95	32	600	37	26	45	69	12	5022	23971	59982	1320	6301	15770
2624	9982	100	30	600	37	25	44	74	12	5985	29956	69964	1573	7874	18394
18,394	69,964														

[1] http://www.recons.org/census.posted.htm : 20 G stars within 10pc and 70 FGK stars within 10pc.

[2] from SIM Book, assumming sun-mass star and earth mass planet:

SNR Target 5.8 from SIM book, for 1% FAP

Slew Time 100 sec



The semi-amplitude of the angular wobble, α, of a star of a given mass, M_*, and distance, D, due to a planet of a given mass, M_p, orbiting with a semi-major axis, a, is given by:

$$\alpha = 3.00 \frac{M_\odot}{M_*} \frac{M_p}{M_\oplus} \frac{a}{(1\ \text{AU})} \frac{(1\ \text{pc})}{D}\ \mu\text{as}$$

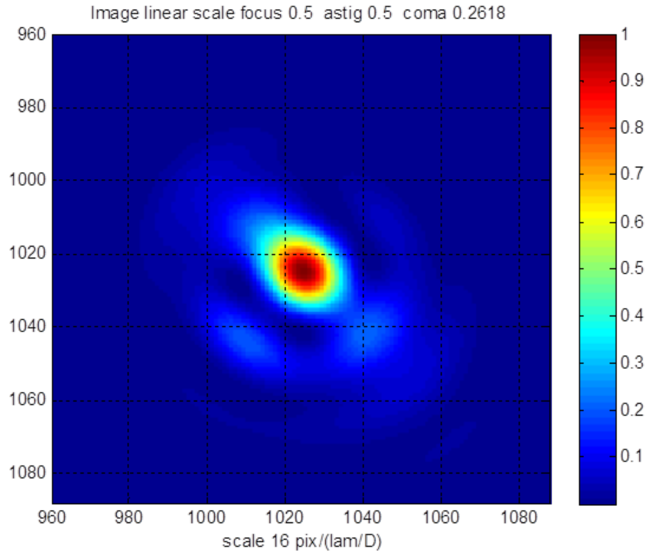
The benchmark case is an Earth-mass planet orbiting 1 AU from a solar-mass star located 10 pc away. For such a planet, the astrometric semi-amplitude, α, is 0.3 μas. Using specially chosen and vetted

Also Powerful tool for Targeted Search

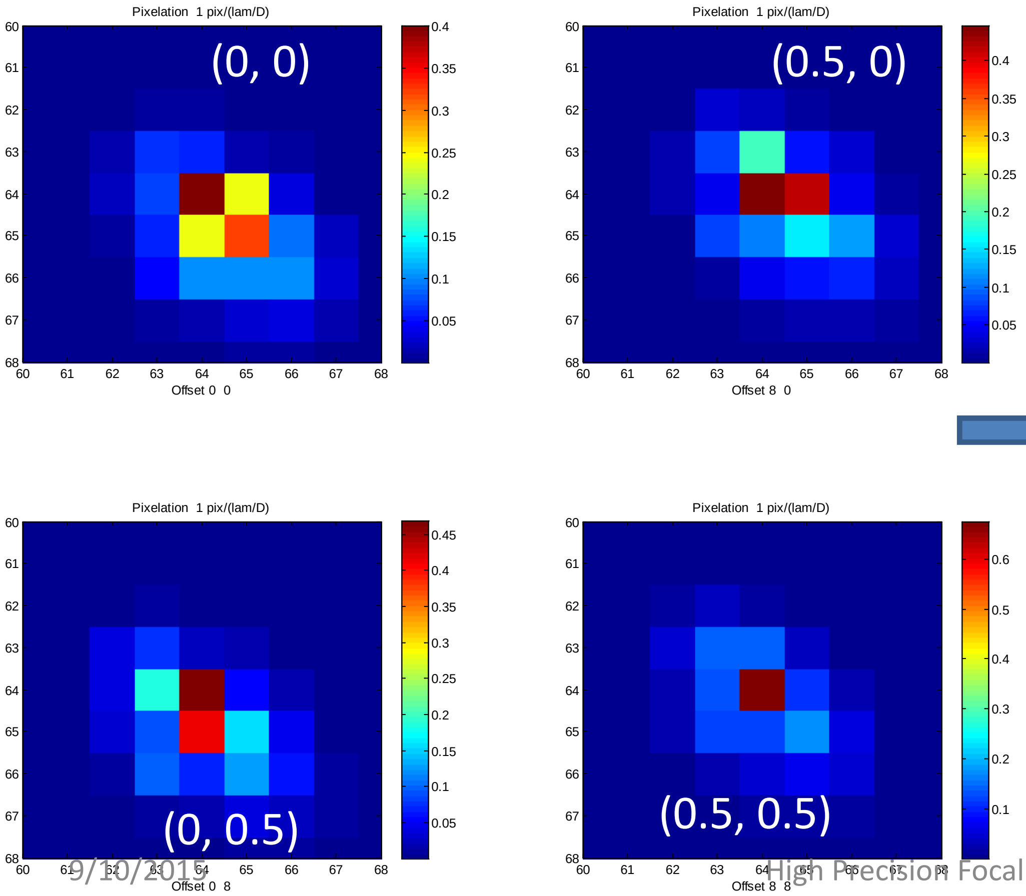
- HDST, armed with precision astrometry, can dramatically enhance existing exoplanet science instruments
  - Transits
    - Transits can get size, but not mass
  - Radial Velocity
    - RV searches yield planet masses that are lower limits (M Sin *i* ambiguity)
  - HDST precision astrometry can
    - characterize exoplanet systems, with masses and orbits (including inclinations) down to the sensitivity needed for Exo-Earths
    - Search all existing G stars within ~ 50 pc (about 2000 G stars) in a little over 1 yr

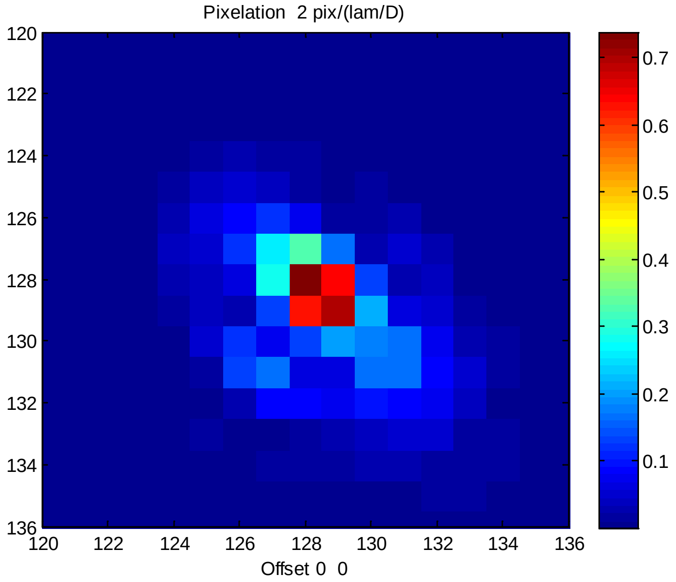
BACKUP

Start with asymetrical PSF



Example, use 4 ditherred undersampled images to generate one nyquist sampled image

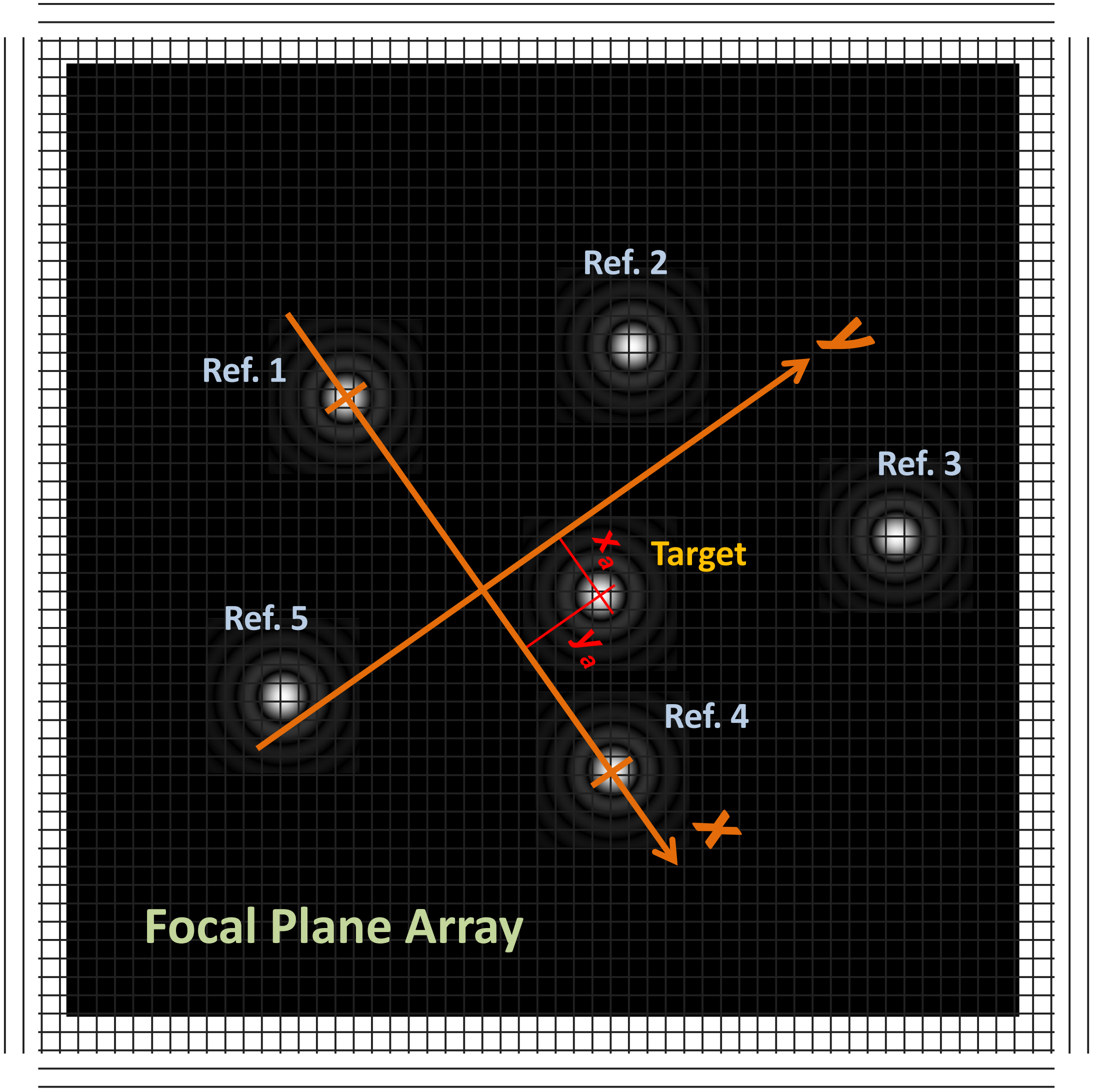




Extreme Focal Plane Calibration (benefits)

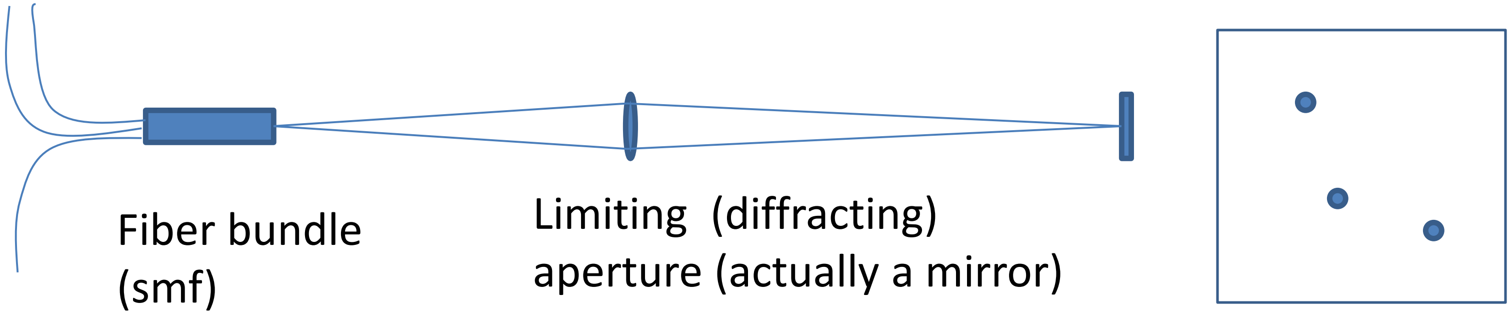
- **Astrometry at ~ 1~10uas**
- **photometry** at 10^{-4}~$\mathbf{10^{-5}}$. (can’t do astrometry at 1e-5 pix without photometry)
  - This is **Kepler** level photometry (if photon statistics allow)
- **Correction of asymetrical PSFs** in images of Galaxies for **Weak Lensing**

- If the spatially varying PSF also changes in time (over weeks/months) that can be tracked as well.


Ref. 2
Ref. 1
Y
Ref. 3
x_a
Target
Ref. 5
y_a
Ref. 4
X
Focal Plane Array

Projecting Point Source PSFs

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



Fiber bundle (smf)

Limiting (diffracting) aperture (actually a mirror)

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

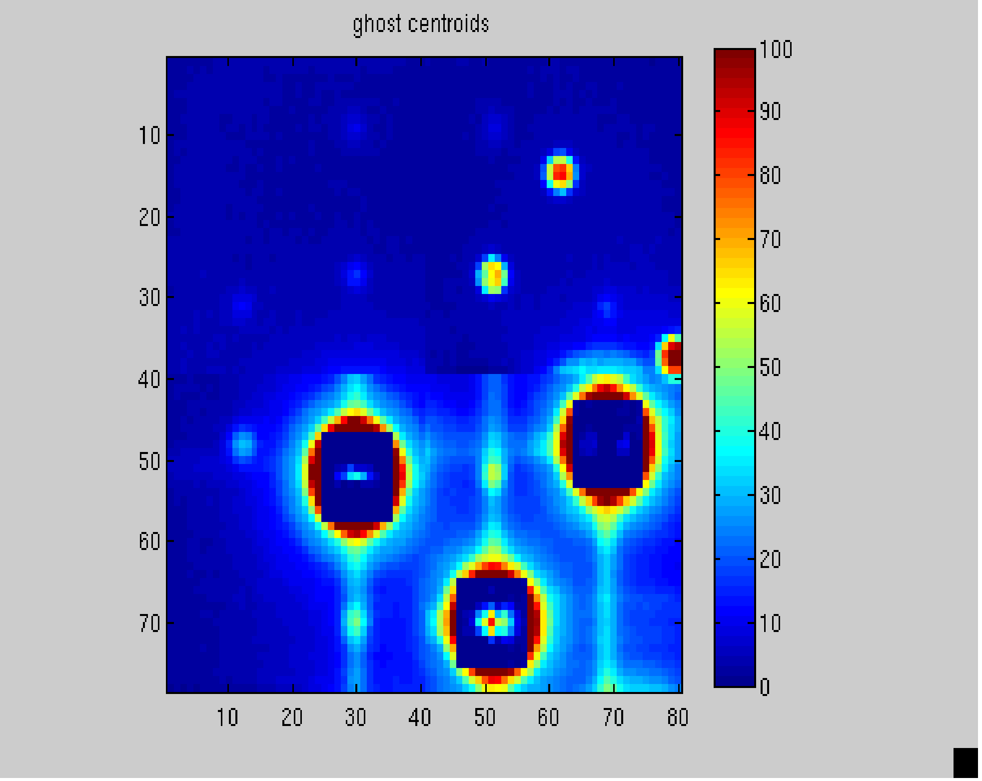
That optic is not perfect $\lambda/100$, the airy spot is not exactly the bessel function(squared). But since all the images use the same part of the same focusing optic, **all the PSFs are identical**.

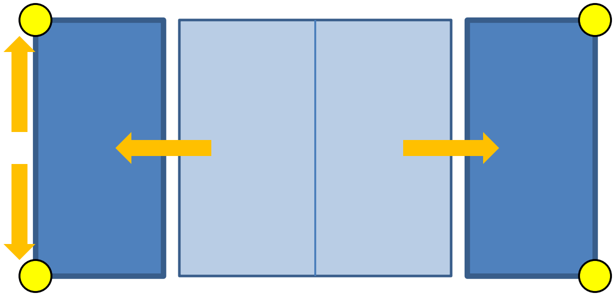
Ghost Images

We noticed ghost images in our setup. At first we looked for stray light reflections (eg window on the detector)

But when we looked at how the ghost images moved relative to the real images, we realized that these ghosts were the result of **electrical xtalk** between the **4 read amps** on the chip.

Our setup at JPL and our colleague's setup in Grenoble used the same E2V chip but totally different readout electronics. But saw similar ghosts.

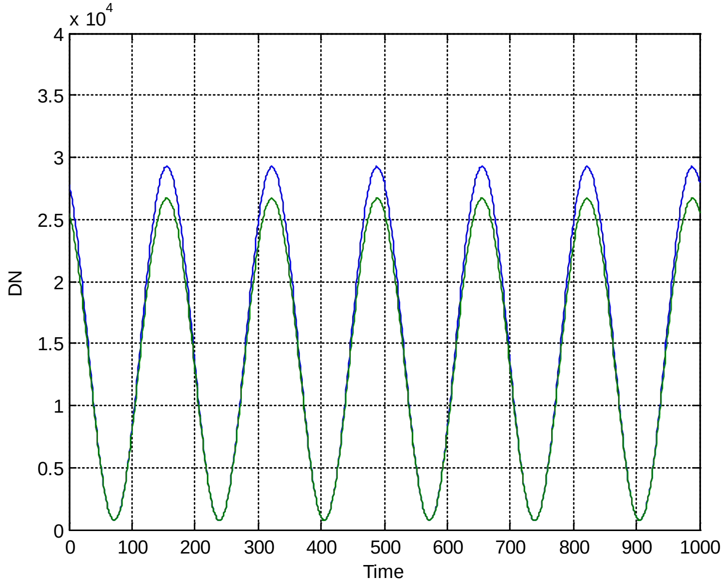




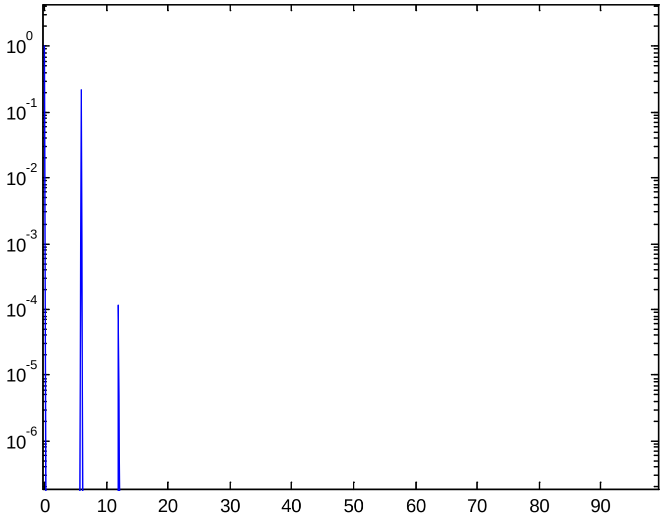
Chip
Rotated 90deg
Wrt movie

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.



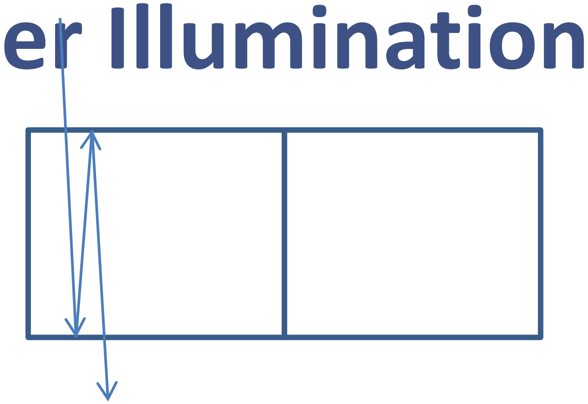
A quick test of photometric nonlinearity is the appearance of a 2nd harmonic. When taking A temporal FFT.



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.

Internal Fringes from Laser Illumination

- With CCDs, at long wavelengths, the detectors are semi-transparent.
- A flat field measurement in laser light (especially at long λ) will exhibit “fringing” that is absent in a white light flat field at the same wavelength.
- The solution is to use a **tunable laser**, and repeat the detector calibration measurements across enough different wavelengths to average this effect away.



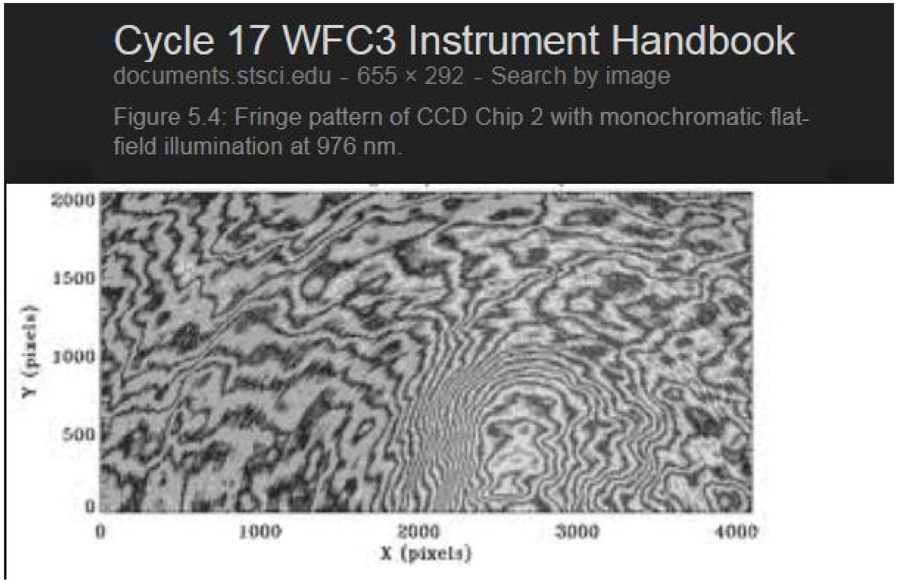


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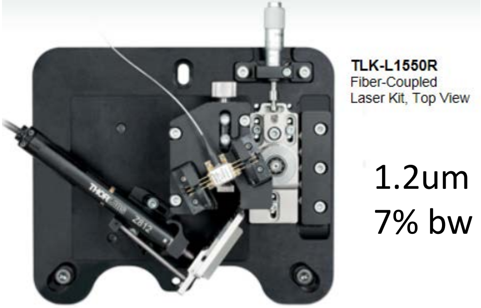
Figure 5.4: Fringe pattern of CCD Chip 2 with monochromatic flat-field illumination at 976 nm.

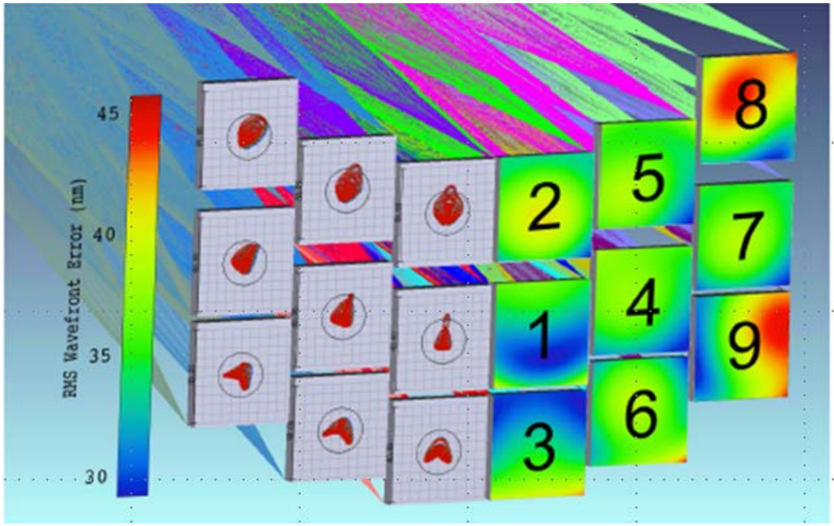
Image found via Google search



1.2um

7% bw

Subpixel Calibration and Weak Lensing



The PSF of the AFTA TMA telescope varies across the FOV.

The spatially varying PSF can be calculated from on orbit data, if every pixel is characterized on the ground before launch.

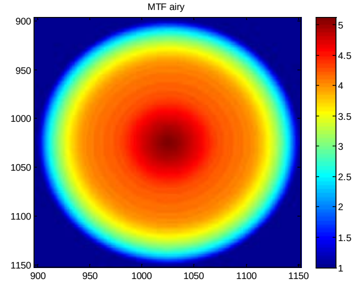
FOV ~0.28 sqdeg
0.38*0.75 deg

There are many 100's of 17 mag stars in the WFIRST FOV and the spatially varying PSF can be measured at every star location.

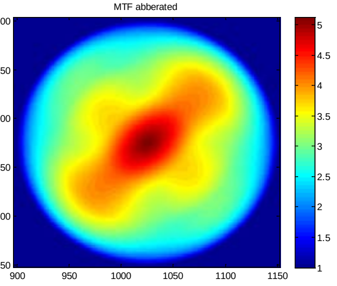
$$\text{FFT(fixed\_image)}= \frac{\text{FFT(image) * FFT(PSF\_symetric)}}{\text{FFT(PSF\_actual)}}$$

- PSF asymetry in images of resolved objects can be removed with conventional fourier deconvolution techniques.
- Sub-pixel calibration becomes more important when the image is undersampled.

MTF of
Airy fn



MTF of
Aberrated
PSF



Overview of Calibration

- The technology described here is subpixel calibration of detectors, at a level that would enable 10-5 l/D astrometry, but also photometry and correction of field dependent PSF at a similar level.
- Sub-pixel calibration is essential for astrometry accuracy < 10-3 pixels, but it is even more important when the focal plane is NOT Nyquist sampled such as for WFIRST.
- This approach to high accuracy astrometry is different than the approach used where pixelation errors are “averaged” by moving the image across many (1000’s of pixels) The two approaches can be combined (they are not mutually exclusive). In our case we move the images to 10’s of positions instead of 10’s of 1000’s of positions.
- The basic idea is to measure the sub-pixel imperfections of detectors, and develop the math/algorithms to incorporate that calibration data into photometry, astrometry, and shape (psf deconvolution) applications.