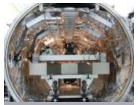
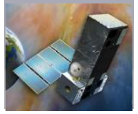




Calibration of Color Dependent Bias and Status of Engineering Risk Reduction for SIM

M. Shao, B. Nemati, C. Zhai, R. Goullioud, J. Marr

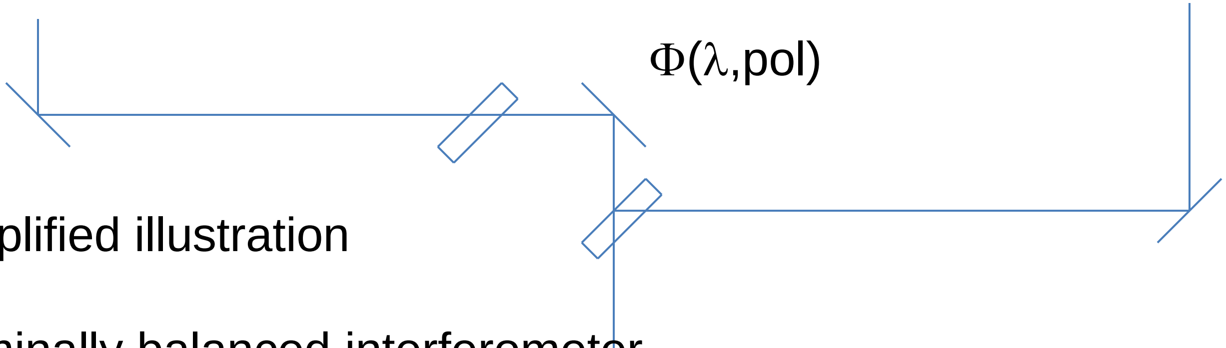
JPL

ELSA Conf June 2010

NORTHROP GRUMMAN
Space Technology
JPL
CALTECH

Outline

- Color Dependent Errors

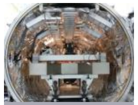


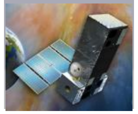
Simplified illustration

Nominally balanced interferometer
Beam splitter transmission is balanced by Compensator plate
But not balanced at the picometer (~50 nanoarcsec) level

- Engineering Risk Reduction, building brassboard components and subsystems that are form, fit, function for space. (survive launch and space environment while maintaining performance)

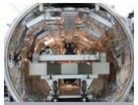
Calibrating Color Dependent Biases



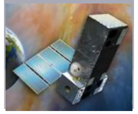


- SIM utilizes “chopping”. The science interferometer chops between ref star(s) and target star to remove a large range of systematic errors.
- But a systematic error that is due to a “color” dependent bias will not chop out if the ref star is of a different spectral type than the target star.
- To detect an Earth Clone @ 10pc, we need the end of mission error for SIM to be ~50 nanoarcsec. (Giving a SNR=6 for a 0.3 uas signal)
  - 50 nas is ~ $2.4\text{x}10^{-13}$ radian or 1.5 pm (picometer) for a 6m baseline
- 50nas is needed after 100’s of hours of observation, over the 5 year mission. The change in star color we want to accommodate at 50 nas is K5 to F5. (4500K to ~7500K)

Types of Color Dependent Biases

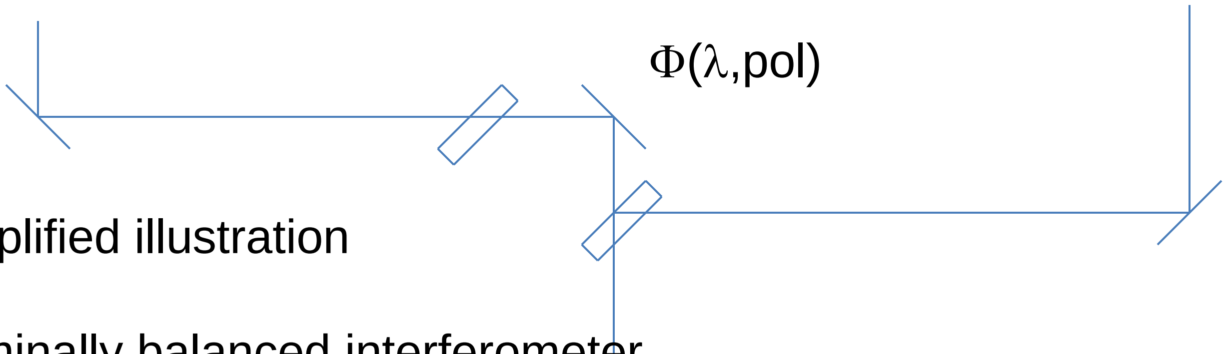


- Material dispersion (identified from the very beginning of SIM), the simplest to calibrate
- Geometric errors : CDCS (color dependent centroid shift of the angle trackers that keep the two arms aligned)
- Wavefront error in the fringe detector.



Material Dispersion

- The two arms of the Interferometer are not exactly identical.



Simplified illustration

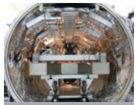
Nominally balanced interferometer
Beam splitter transmission is balanced by Compensator plate

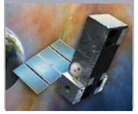
Imblance remains at:

1) 1 extra mirror in left arm
2) Left arm has 2 AR coatings vs 1 in right arm before combination
3) Transmission through BS vs Reflection through BS

We made a decision to design the optics (and coating) to build SIM with Material dispersion < ~20nm p-p between 450nm and 900nm. And do everything else through calibration. (~2nm OPD shift from 4500K ~7500K)

What if We Did Nothing?

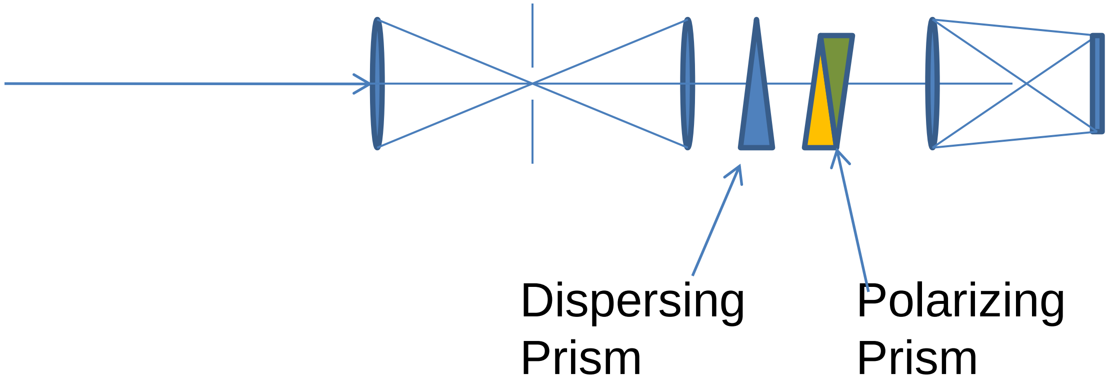




- We wish to measure the motion of the target star with very high accuracy?
- The OPD change is ~1nm when the color of the star changes from ~4500 (K giant ref star) to 5700K (G target star).
  - 1nm/6m ~ 30 uas. But for relative astrometry this fixed bias is not a problem if we adopt the same observing pattern at all epochs.
  - The G star would appear 30uas to the left of where it actually was, but it'd be the same 30uas at every epoch.
- If we wanted 2~3 uas accuracy, maybe nothing needs to be done.
- The error for exoplanets (and parallax/prop motion) occurs only if the color of the star changes over epochs. Since we eventually want 30~50 nas precision, we have to calibrate material dispersion.

SIM Fringe Detector

- After the light is combined, the fringe detector is a low resolution polarizing prism spectrometer.

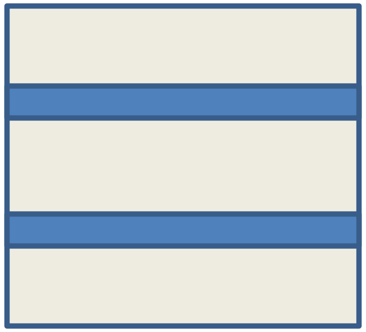


450-900nm
80 pixels

Dispersing Prism

Polarizing Prism

Fringe modulation with PZT, measured with laser metrology with picometer precision.



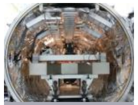
S polarization

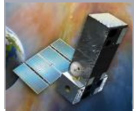
P polarization

450nm 900nm
CCD 80*80 pix

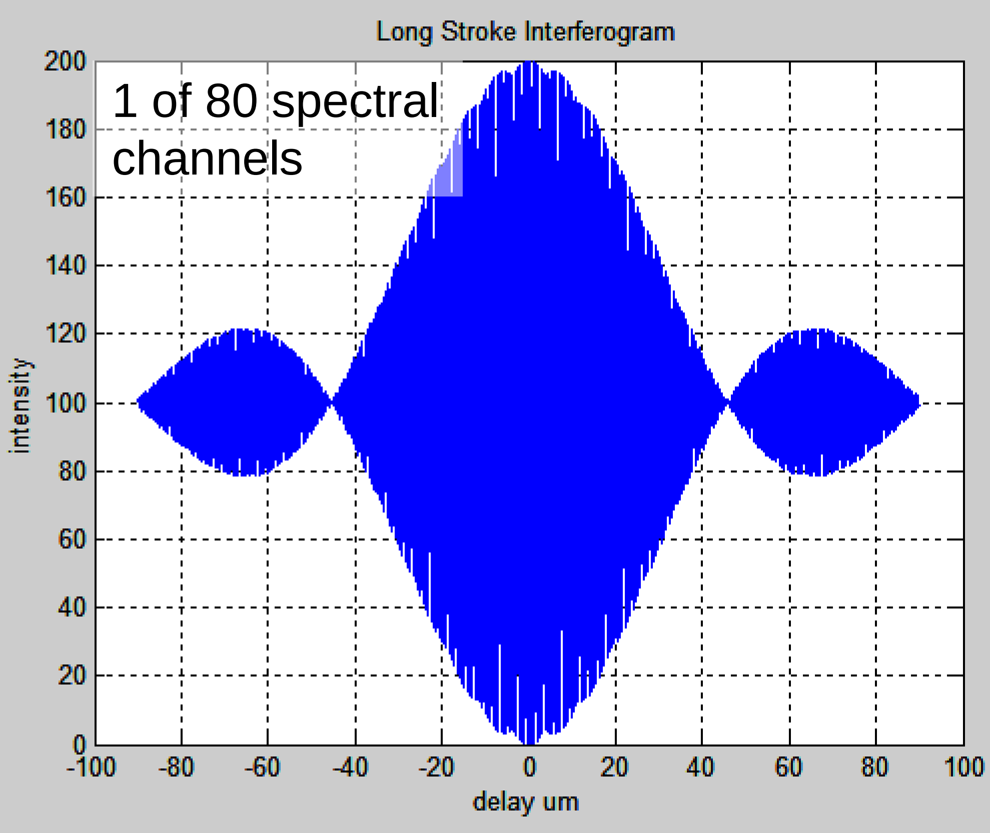
Stars @ 1Kpc are slightly ~1% polarized by interstellar dust

Calibration of Material Dispersion

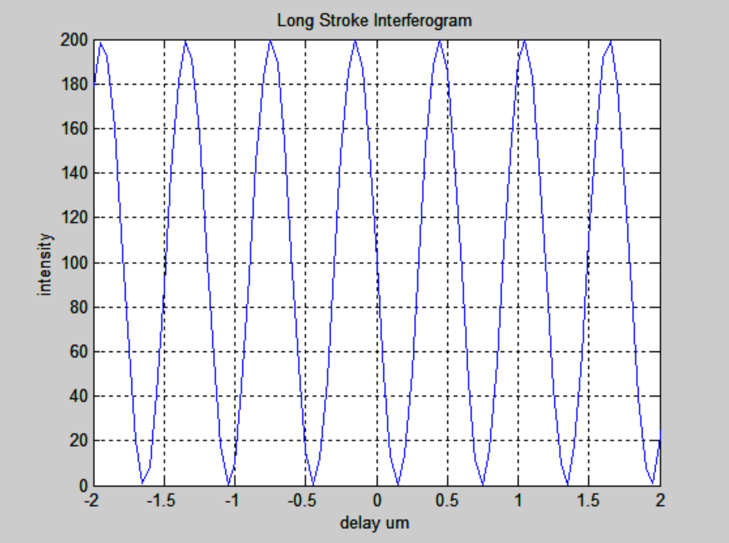




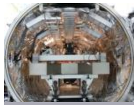
- With an internal white light source, record the interferogram for a ~100um change in OPD (in ~50nm steps) for each of the 80 spectral channels in the low resolution spectrometer.



1 of 80 spectral channels

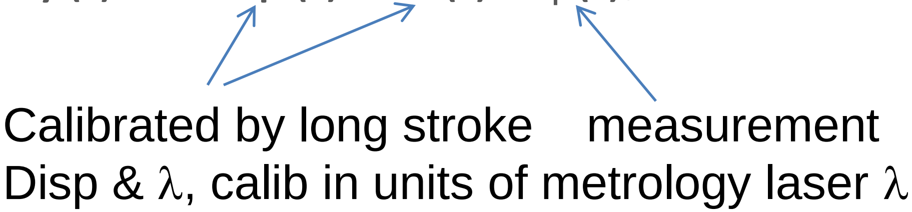


Long stroke interferogram gives us the complex spectral response of each spectra pixel.
Effective wavelength
Spectral width
Phase dispersion



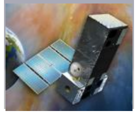
Dispersion Corrected Delay

- For each spectral channel
  - $\mathrm{Delay}(i) = \mathrm{Disp}(i) + \lambda(i) * \phi(i)/2\pi$



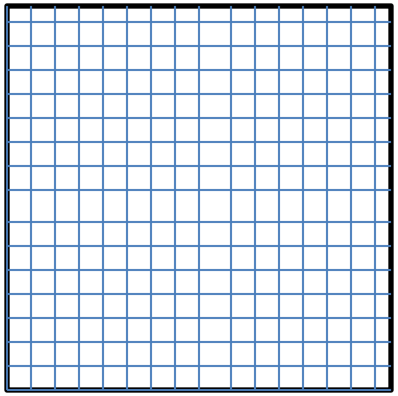
Calibrated by long stroke measurement
Disp & λ, calib in units of metrology laser λ

- $\langle \mathrm{Delay} \rangle = \Sigma\,(\mathrm{delay}(i) * \mathrm{weight}(i))/\Sigma(\mathrm{weight}(i))$
  - Weight(i) determined by photon-det noise
  - Angle ~ <delay>/Baseline



Color Dependent Geometric Errors

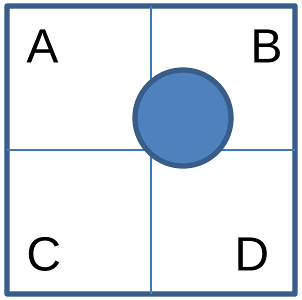
- These errors are due to the effect we call CDCS, color dependent centroid shift, in the tip/tilt sensors that keep the two arms of the interferometer aligned.
  - Describe why the angle tracker shift with color
  - How that shift in alignment changes OPD.



Angle tracker CCD
(currently 1 arcsec pixels)
λ/D ~ 0.25 arcsec images

Because images < pixel
Tip/tilt is measured using the normal quad-cell formula

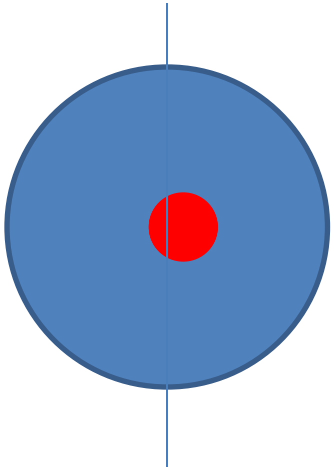
But X in arcsec or radians depends on the width of the image λ/D.



$$X = \frac{(A+C-B-D)}{(A+B+C+D)}$$

OPD Change with tip/tilt Change

- When the tilt of the stellar beam changes, it produce apparent OPD changes in 3 ways.
  - 1) Tilt* offset error
  - 2) Theta^2 error 3) Change spectrometer λ calib

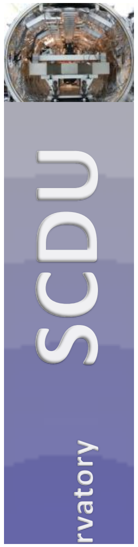


Ideally the metrology beam is at the center of
The starlight beam, so that tilt error in the stellar beam
Does not cause an OPD error.

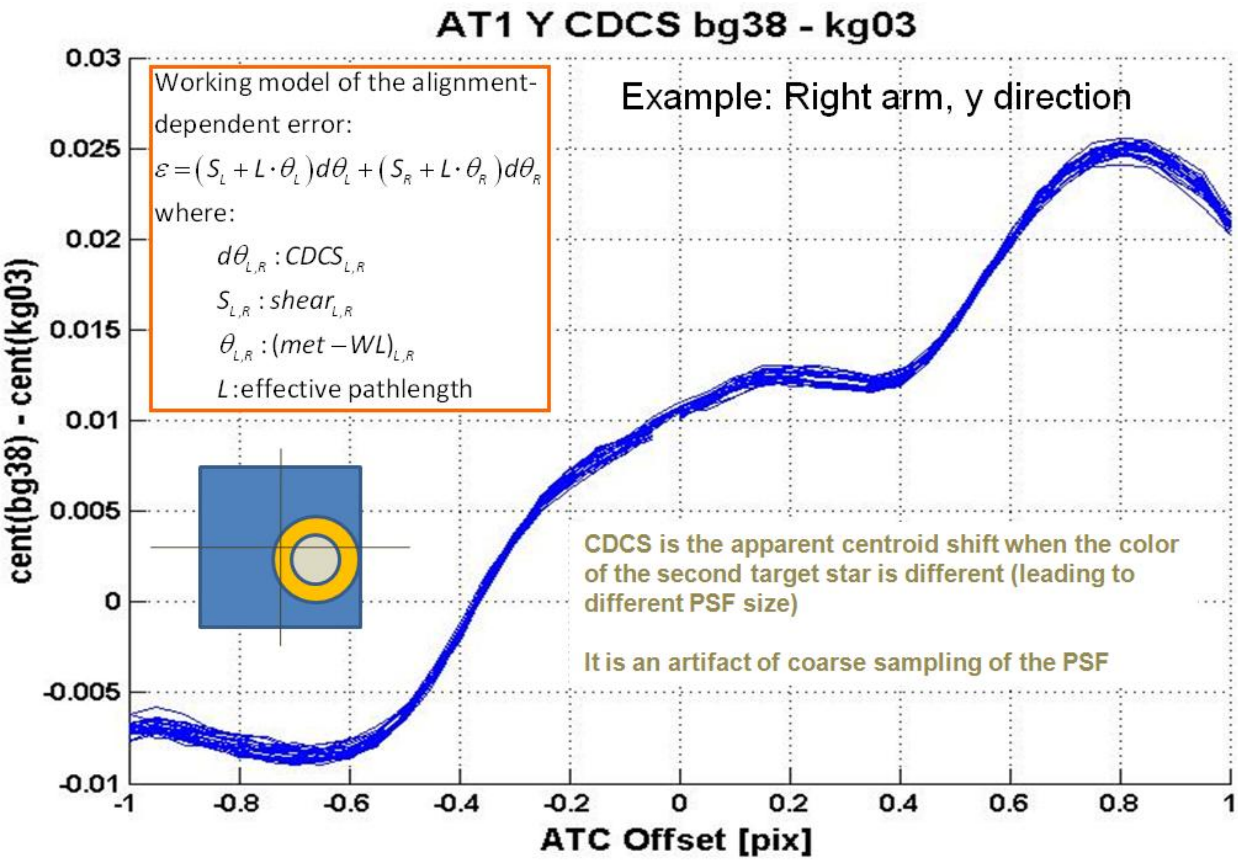
Currently we expect to keep the metrology and starlight centered to ~10um, implying the color dependent tilt has to be < ~1e-7 radians, or ~1/150 of λ/D.

The 2nd geometric error comes from an angular deviation of the Stellar beam vs the metrology beam, error = θ^2*L.
Note a geometric error that is NOT color dependent will “chop out”, we only have to worry about the color dependent part of this error, due to a change in tilt from CDCS.

SCDU Top Improvements - I



- **Color Dependent Centroid Shifts (CDCS)** cause a color
  - We quantified, cal
    CDCS
  - The results was a s
    shear error and be
    consistency



Working model of the alignment-dependent error:

$$\varepsilon = (S_L + L\cdot\theta_L)d\theta_L + (S_R + L\cdot\theta_R)d\theta_R$$

where:

$d\theta_{L,R}$: $CDCS_{L,R}$

$S_{L,R}$: $shear_{L,R}$

$\theta_{L,R}$: $(met - WL)_{L,R}$

L : effective pathlength

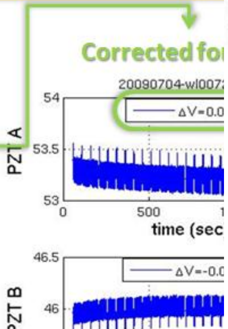
CDCS is the apparent centroid shift when the color of the second target star is different (leading to different PSF size)

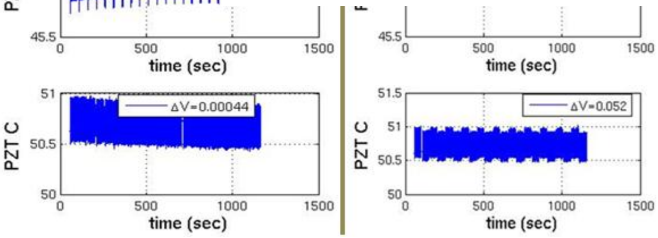
It is an artifact of coarse sampling of the PSF

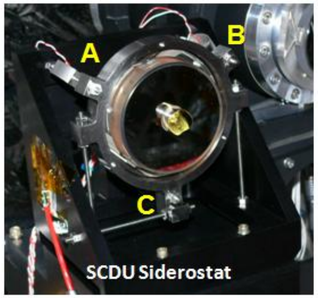
Filter is chang

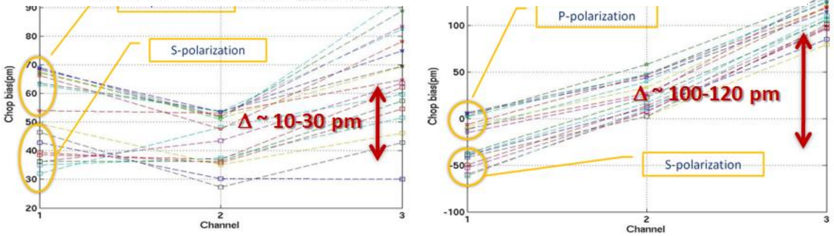
Uncorrected: PZT voltages change by 0.1 V ; pointing change between filters is about 0.2 urad

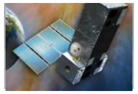
Corrected: PZT voltages change by < 0.005 V, CDCS has been corrected to better than ~ 0.01 urad



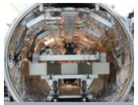


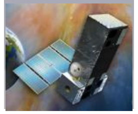






Correcting CDCS

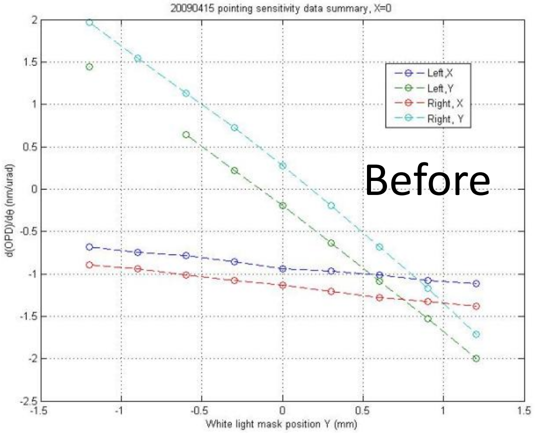




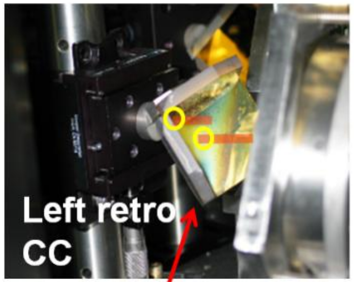
- CDCS biases are large because the PSF is undersampled by the CCD camera.
  - We’re increasing the pixel density critically sample the PSF. (2 pix per λ/D)
- The fringe detector is an 80 channel spectrometer, so SIM measures the spectrum (and we can calculate the change in the shape of the PSF for different color stars, with one more piece of information)
- The PSF at the angle tracker CCD is non-ideal primarily due to wavefront errors in the optics (~lambda/10). We need CDCS < 0.005 λ/D so knowledge of the wavefront to $\lambda/200$ is sufficient. (we expect the optics to stable << $\lambda/200$, so this is a 1 time calibration during construction/alignment) Currently we’re planning to use focus diversity (in/out of focus images) to derive the wavefront errors.

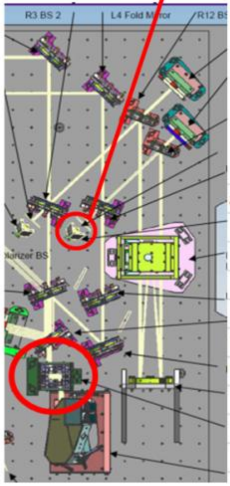
SCDU Top Improvements - II

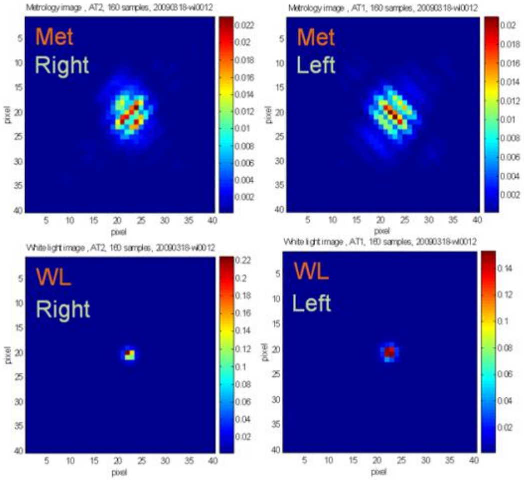
- **Shear** between metrology and white light causes sensitivity to pointing errors and couples with CDCS to cause bias.
- We also significantly improved Metrology – White Light Angle Alignment.



Before

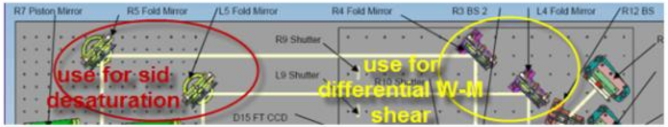


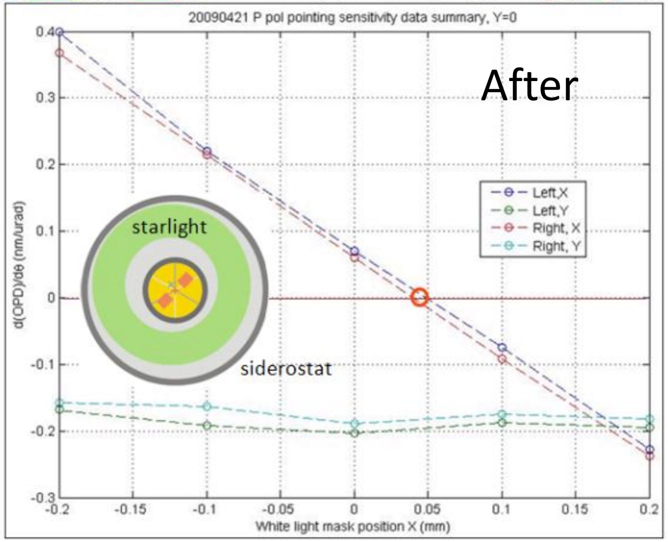




after adjusting D3 to aligned (using R as matching criteria)

	R		L		
	x	y	x	y	Units
White Light	-3.992	-1.900	-3.960	1.999	pixel
Metrology	-3.995	-1.893	-3.876	2.129	pixel
WL-Met angle deviation	0.003	-0.007	-0.084	-0.130	pixel
WL-Met angle deviation	0.12	-0.28	-3.36	-5.2	urad
WL-Met radius (urad)	**0.3**		**6.2**		urad
Right-Left (urad)	**3.48**	**4.92**	Consistency between R & L arm misalingment data		urad
(R-L)-radius (urad)	**6.0**				urad





After

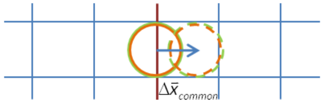
Wavefront Error

- With a perfect wavefront, the central lobe of the airy pattern has zero phase and the 1st ring pi phase, etc. With an imperfect wavefront (eg l/20) the wings of the diff pattern will have phase errors comparable to lambda/20 ~30nm.
  - At a given pixel in the spectrometer, most ~60% of the light is from the wavelength band for that pixel, but 20% of the light is from wavelengths that should have landed in an adjacent pixel. If the spectrum changes, the amount of light from the adjacent pixel changes. We're sensitive to a 1pm effect out of 30nm.
- The effective dispersion we see is a sum of material dispersion and wavefront error * diffraction.
- The result is that the spectrometer has to be several times more stable than if we just had to calibrate material dispersion. (eg a particular pixel is 600nm +/- 0.01nm)

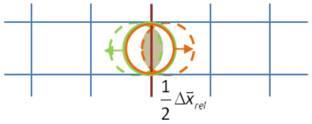
SCDU Top Improvements - III

- **Fringe Placement** turns out to be a very important parameter: if the fringe moves after a long stroke, it corrupts the calibration.
- We developed the capability to measure the placement precisely, then measure the sensitivity, and finally control fringe placement
- At this time, our capability placement to ~ 2 milli-pixels

common-mode motion
affects the applicability of
the long stroke calibration

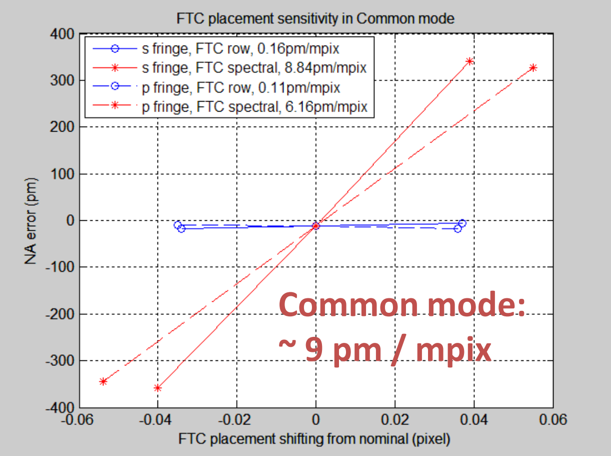


differential/relative motion
in the presence of a non-flat phase
profile causes a phase error

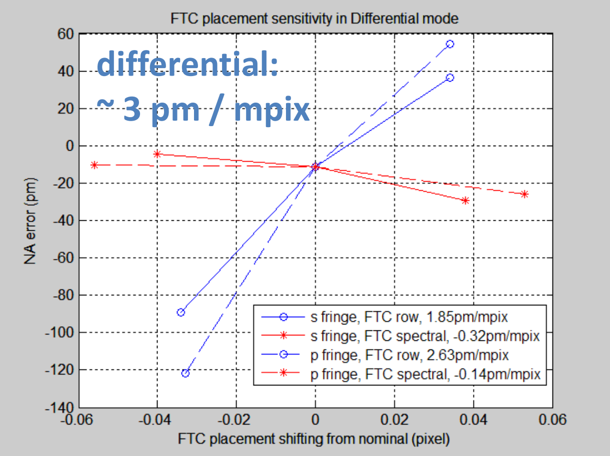


$$\delta_{tot} = \left(\hat{i}\frac{\partial}{\partial x_{com}} + \hat{j}\frac{\partial}{\partial y_{com}}\right)\varepsilon_{spect}\cdot\Delta\vec{x}_{common} + \left(\hat{i}\frac{\partial}{\partial x_{rel}} + \hat{j}\frac{\partial}{\partial y_{rel}}\right)\varepsilon_{WFE}\cdot\Delta\vec{x}_{rel}$$

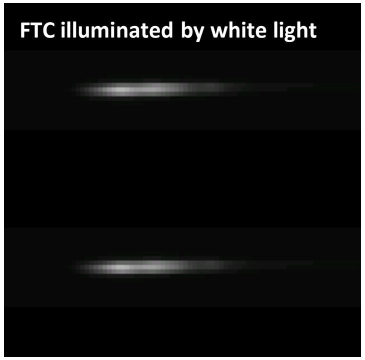
$$= \vec{\nabla}\varepsilon_{spect}\cdot\Delta\vec{x}_{common} + \vec{\nabla}\varepsilon_{WFE}\cdot\Delta\vec{x}_{rel}$$

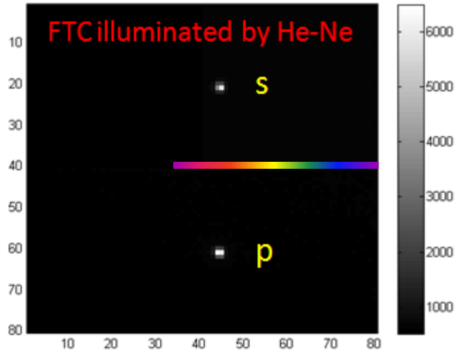


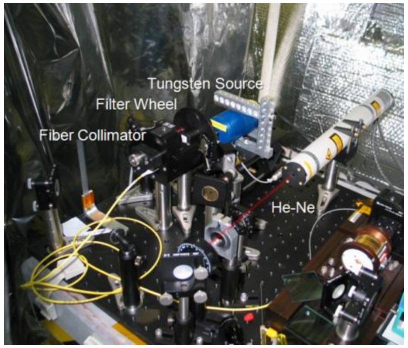
Common mode:
~ 9 pm / mpix



differential:
~ 3 pm / mpix

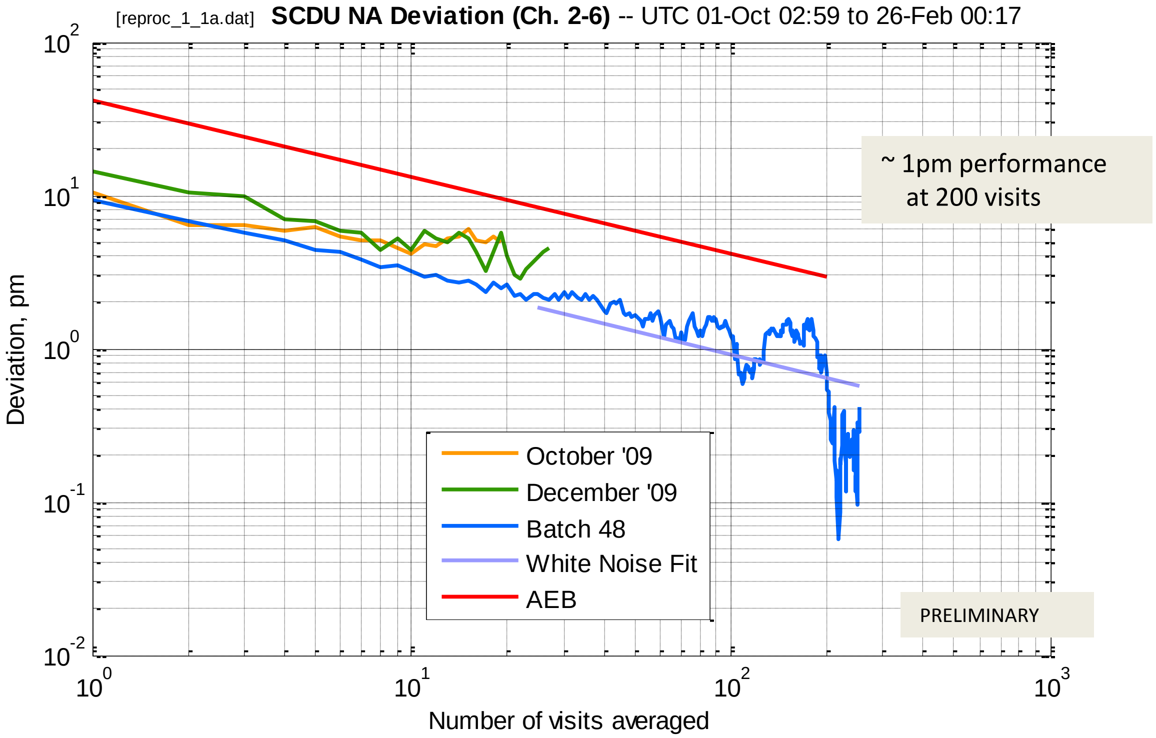

FTC illuminated by white light


FTC illuminated by He-Ne



SCDU NA Performance Summary

- When all the calibrations are applied, we have experimentally demonstrated that the color dependent effects an be modeled to ~ 1picometer ~ 30 nanoarcsec, for long integration times.
- The calibrations we do on the ground, and on orbit, are closely tied to how we plan to analyze the data. (Ground and on orbit calibration and data analysis is viewed as different parts of 1 task.)

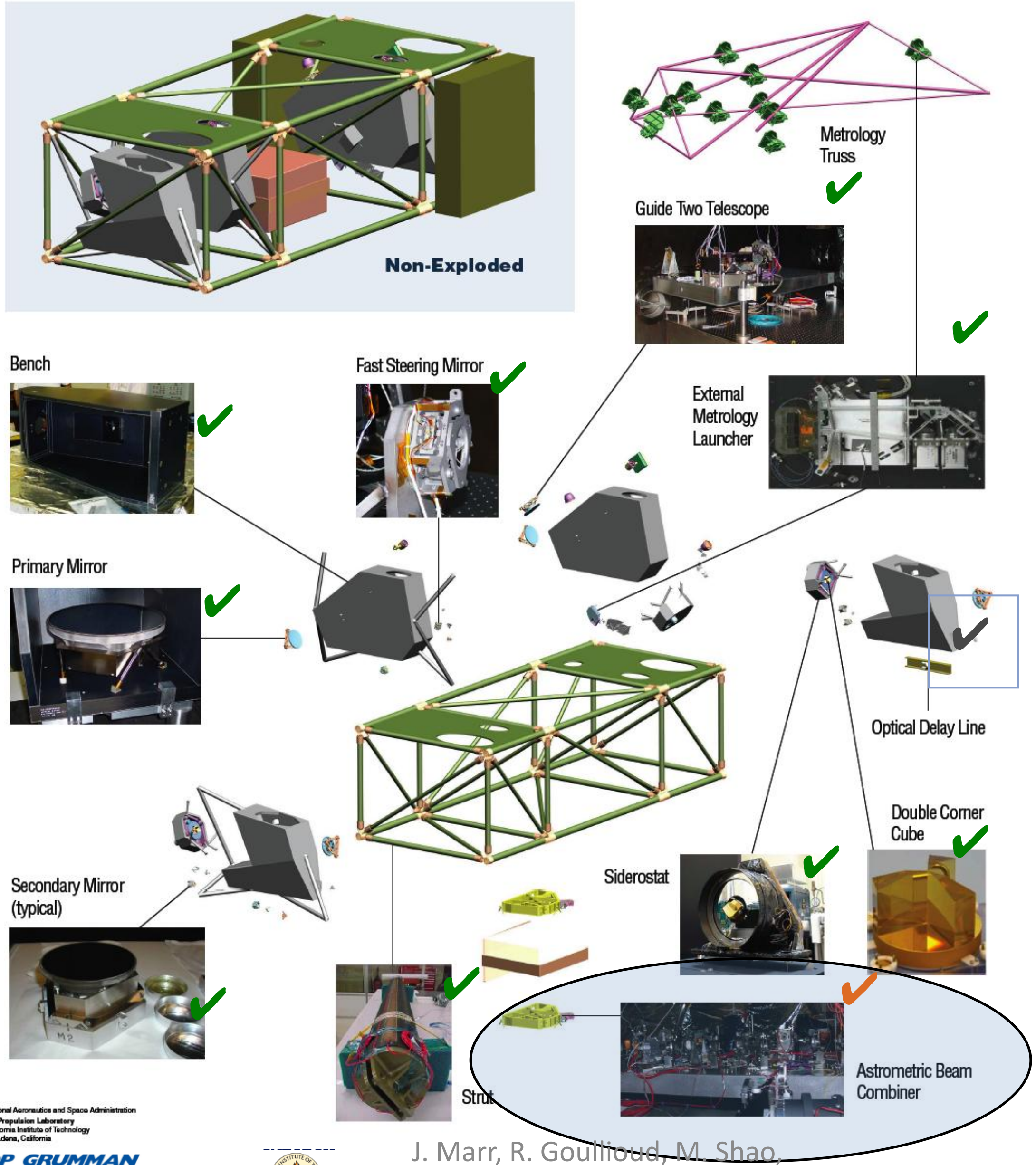


~ 1pm performance
at 200 visits

PRELIMINARY

SIM Lite Brassboard Status - Today

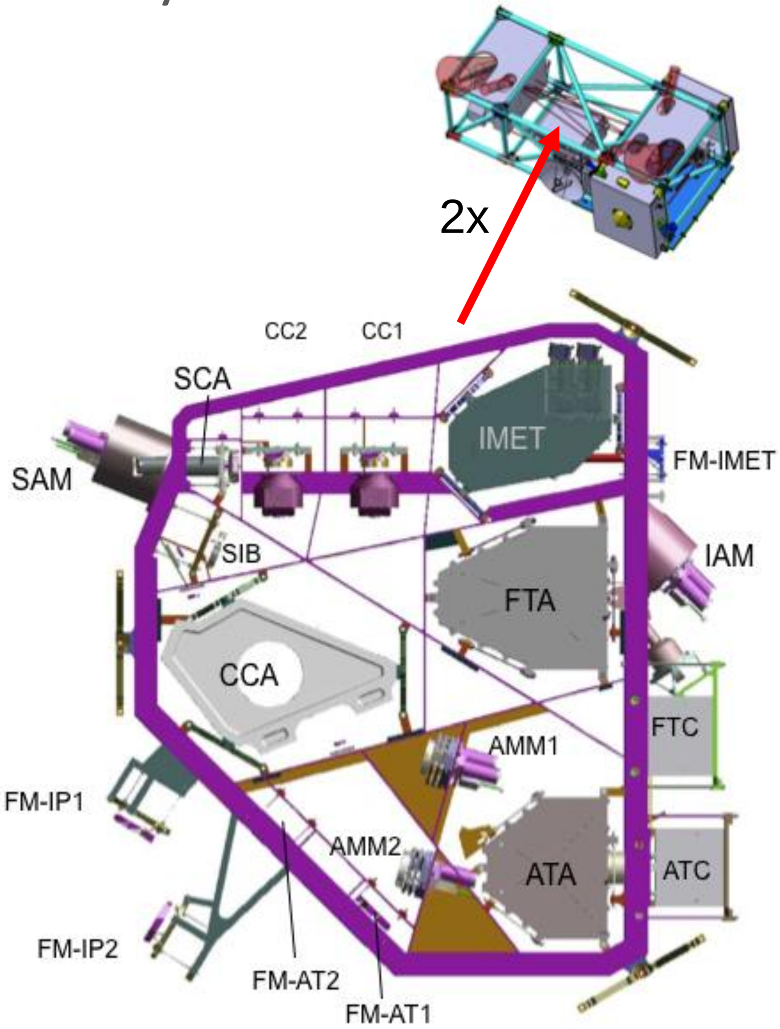
- Brassboards – form, fit and function to flight
- **Completed:**
  - Guide-2 Telescope.
  - Internal & External Metrology beam launchers.
  - Fine Steering Mirror.
  - Beam Compressor & Bench.
  - Modulation Optical Mechanism (not shown).
  - Pathlength Optical Mechanism (not shown).
  - Double Corner Cube.
  - 30 cm Siderostat mirror.
  - Precision Structure Strut.
- **In process now:**
  - Astrometric Beam Combiner (next 2 pages).
  - Metrology source pump diode assembly (not shown).
- **Planned but not yet started:**
  - Optical Delay Line
  - Siderostat gimbal mechanism.



SIM Lite Astrometric Beam Combiner

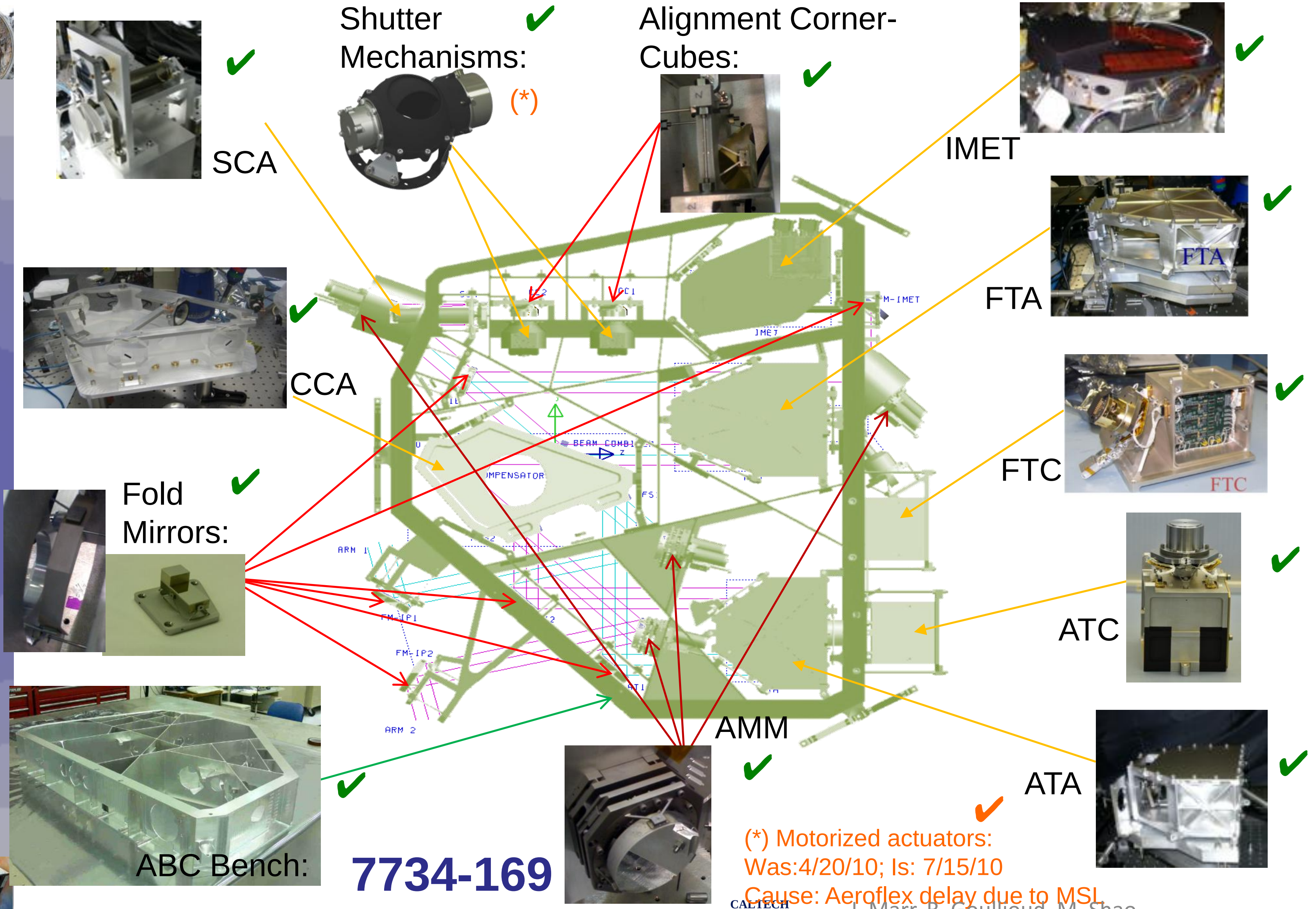
Astrometric Beam Combiner (ABC) Acronyms

AMM1	Alignment Mirror Mechanism on arm 1
AMM2	Alignment Mirror Mechanism on arm 2
AT	Angle Tracker = ATA + ATC
ATA	Angle Tracker Assembly
ATC	Angle Tracker Camera head
CC1	Self-check corner cube 1
CC2	Self-check corner cube 2
CCA	Compensated combiner assembly
FM-AT1	Fold mirror on AT input (arm 1)
FM-AT2	Fold mirror on AT input (arm 2)
FM-IMET	Fold mirror on IMET path
FM-IP1	Fold mirror on input port 1 (arm 1)
FM-IP2	Fold mirror on input port 2 (arm 2)
FT	Fringe Tracker = FTA + FTC
FTA	Fringe Tracker Assembly
FTC	Fringe Tracker Camera head
IAM	IMET Alignment Mechanism
IMET	Internal Metrology beam launcher
SAM	Stimulus Alignment Mechanism
SCA	Stimulus collimator assembly
SIB	Stimulus Injection Beamsplitter
SM1	Shutter mechanism 1
SM2	Shutter mechanism 2



ABC Bench (purple) supports the ABC assemblies.

Astrometric Beam Combiner – Status



SCA ✓

Shutter Mechanisms: ✓ (*)

Alignment Corner-Cubes: ✓

IMET ✓

FTA ✓

CCA ✓

FTC ✓

Fold Mirrors: ✓

ATC ✓

AMM ✓

ATA ✓ ✓

ABC Bench: ✓

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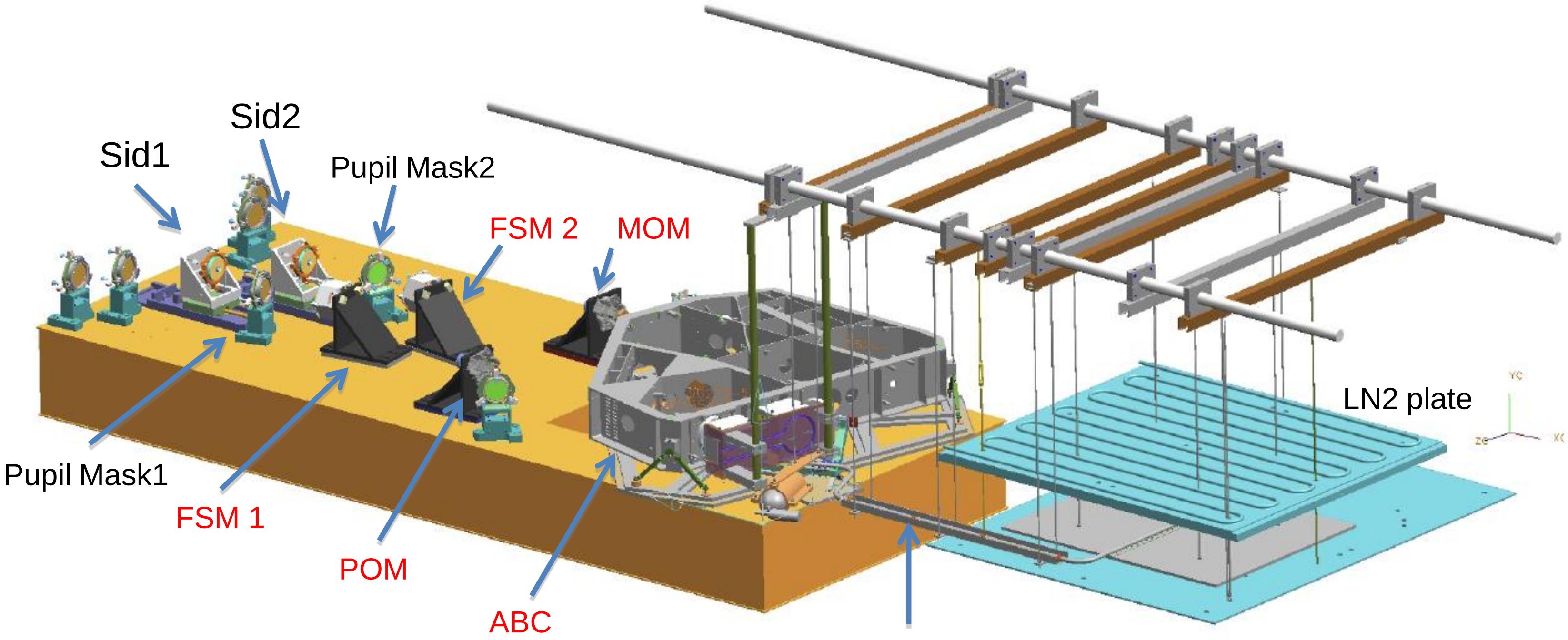
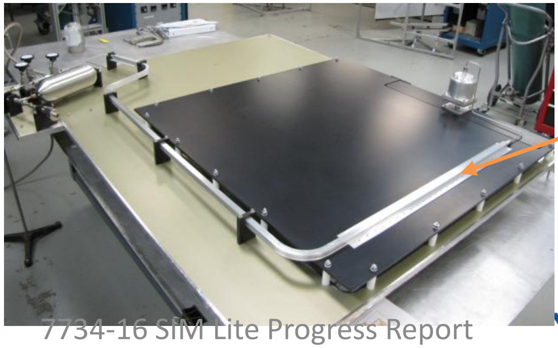
(*) Motorized actuators:
Was:4/20/10; Is: 7/15/10
Cause: Aeroflex delay due to MSL

Brassboard Ineterferometer I&T

- Single Interferometer Test
  - Astrometric, Dynamics & Control (D&C)





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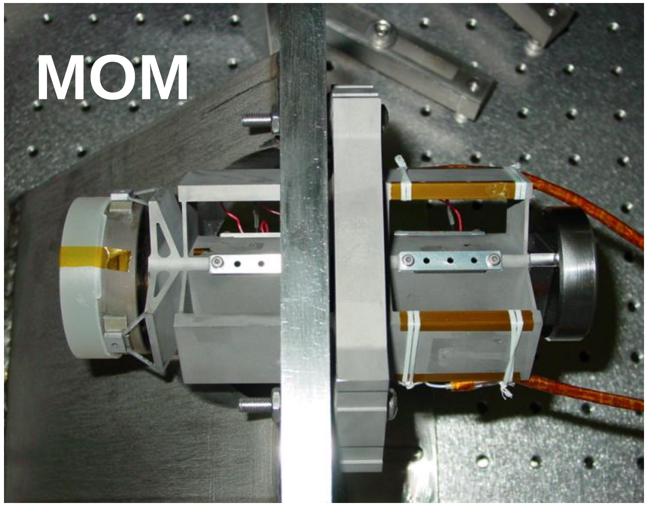
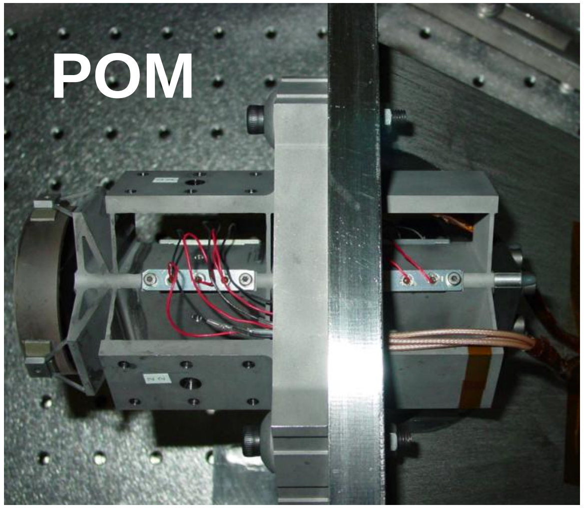
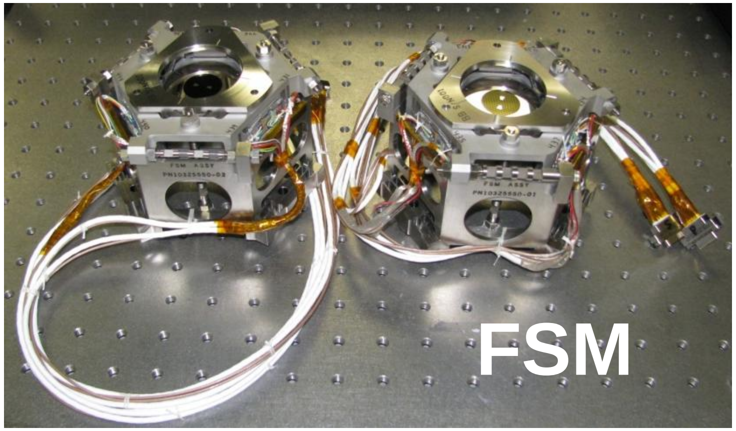
MOM/POM/FSM (Delivered)







MOM = Modulation Optical Mechanism

POM = Pathlength Optical Mechanism

FSM = Fine Steering Mirror

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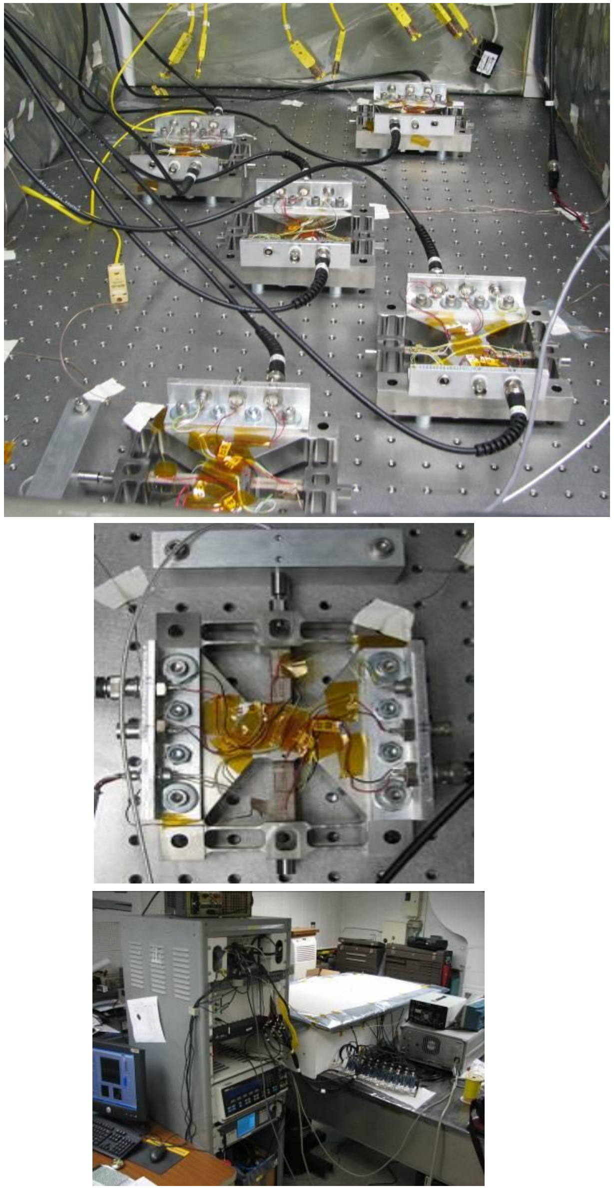
PZT AC Life Test Completed

- PZT AC life test **stopped at 100B** cycles (**~5x one life**) as planned.
  - –20 PZTs in life test.
    - 10 Active; 10 Inactive
  - –~2 to ~3% degradation in deflection at end of life; very acceptable.
  - –No failures.
  - –Re-polling of the PZTs at 100V restores full deflection.



Summary

- The spectal calibration of SIM at 0.03 uas level was the last “laboratory” test. (driven by the search for 1 Mearth planets in the HZ around 60~100 nearby stars.) We still have a photon (SNR) limit of 1uas in a 1000 sec observation.
- The project has made considerable progress building flight qualified components and subsystem ~80% of the interferometric/metrology subsystems. (units have survived vibration and thermal/vac and maintained picometer performance.)