Metrology for Space-based Large Apertures

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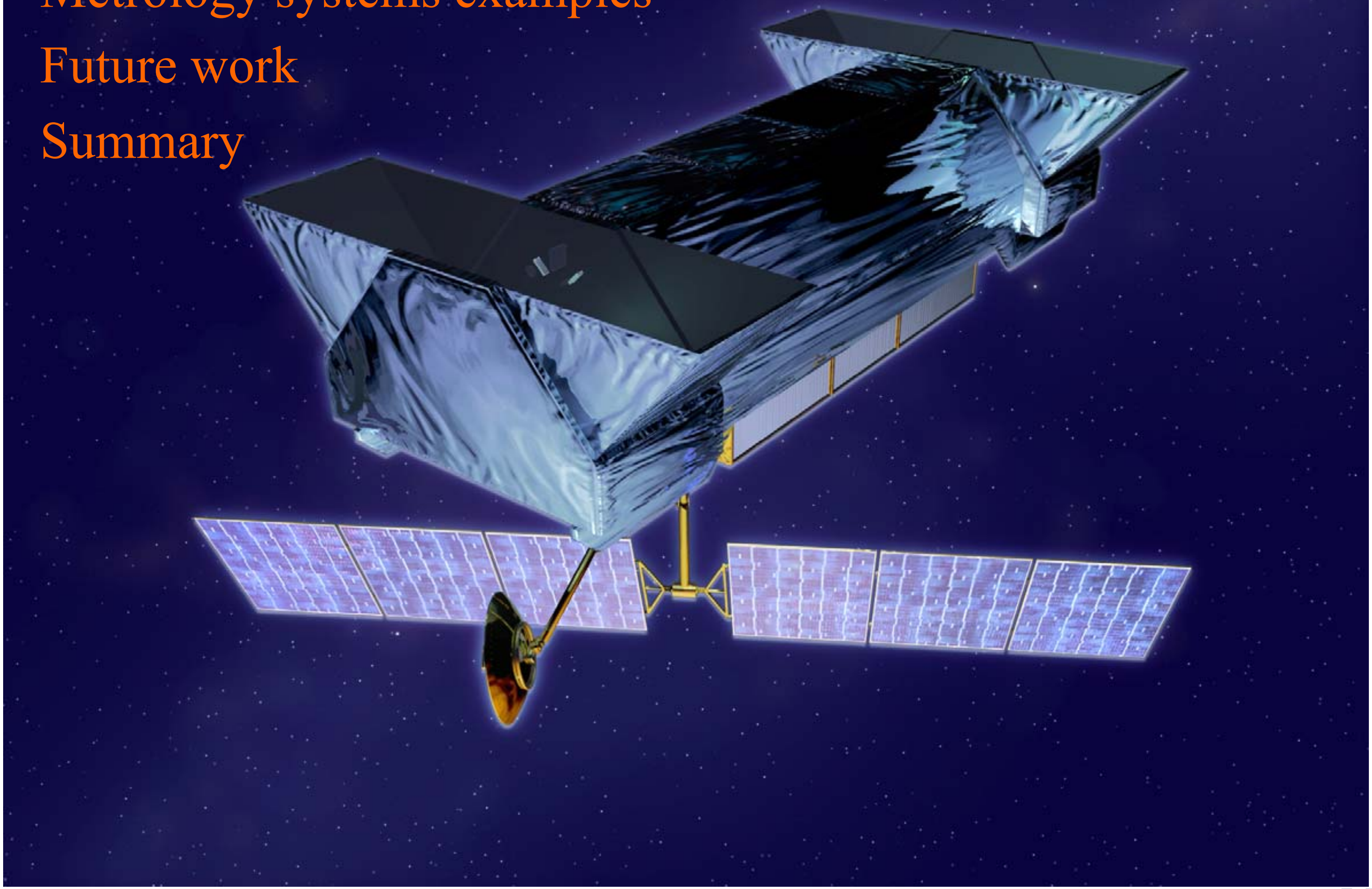
Outline

- Role of metrology in large space based structures
- Metrology systems examples
- Future work
- Summary



Where Metrology Fits?

Option Space:

A: Light-weight, deployable, stable structure with no or limited metrology, to

Z: Low-cost structure and a very capable metrology system to correct for deformations.

Where is the optimum?

- Mechanical scaling law:
  - Mechanical optical error scales to the 4th power of aperture diameter (Peterson, et al.)

$$\delta \propto \frac{D^4}{h^2} \frac{1}{E/\rho} f(\upsilon) g(P)$$

  - The larger the aperture, the more (a lot more!) challenge on structures

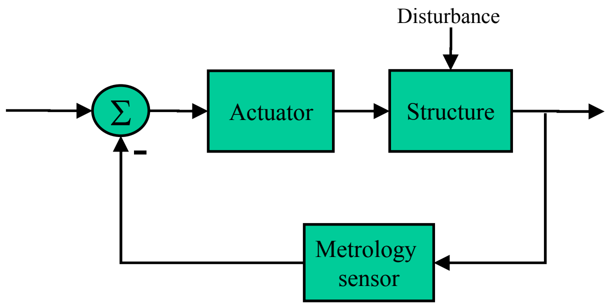
- Metrology sensor scaling law:
  - Metrology sensor error scales linearly with the dimension

$$\delta x_M = \frac{\delta x_R}{\Delta \phi_R} \Delta \phi_M = \frac{\delta x_R}{x_R} x_M$$

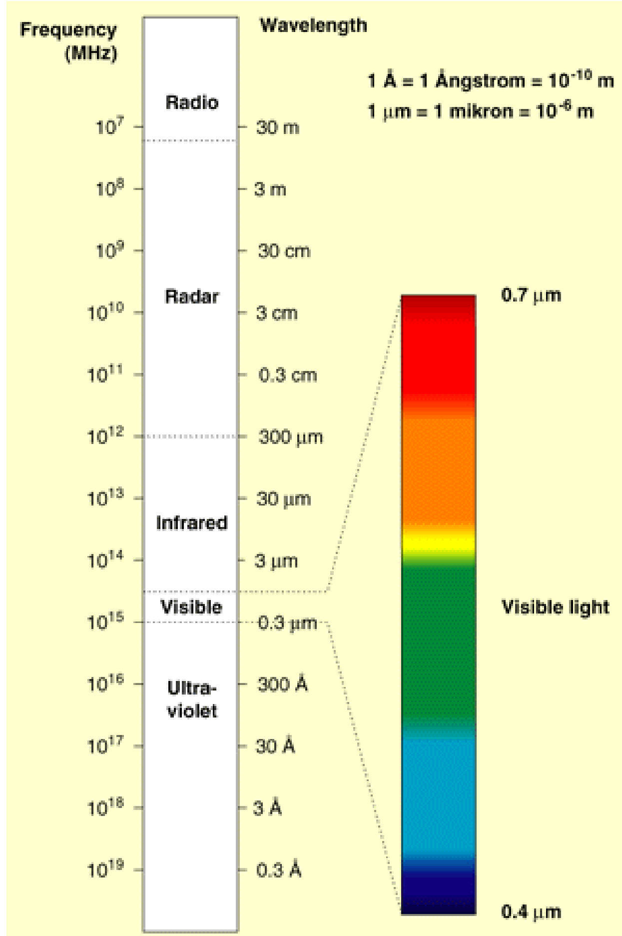
  - Save your $$ and kg from structures to build metrology?

Application-driven Metrology Technologies

- Open-loop: metrology provides knowledge of structure dimension over time and metrology measurement is used in post-processing
- Closed-loop: metrology provides structure deformation measurement which is then used to maintain structure rigidity via controllers and actuators

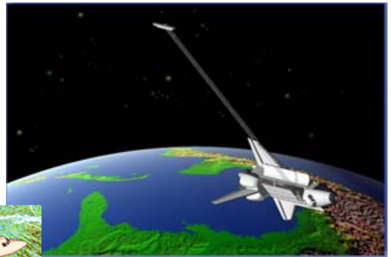


- Dimension of large apertures/structure are stabilized (at least have the knowledge) to a small fraction of the observation wavelengths
- Primary driver of metrology performance:
  - Radar: mm to um metrology accuracy
  - IR/VIS: um to sub-nm
  - Dimension: typically >10m
- Types of metrology measurement:
  - Provide knowledge of absolute distance (abs MET)
  - Provide knowledge of change of distance - displacement (rel MET)



Metrology in Various Missions (Past, Current and Future)

SRTM

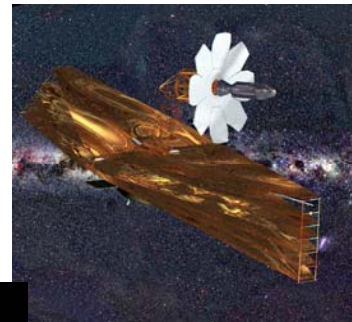


GeoSAR

SIM

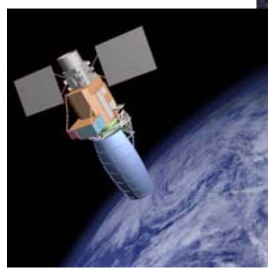
TPF

SAFIR



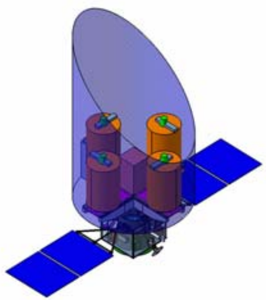
LISA

CAMEO



NuSTAR

DAViNCI

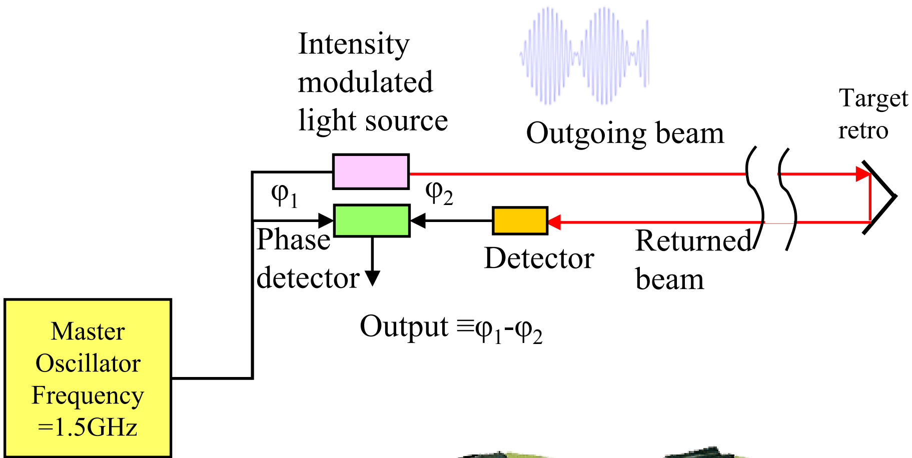


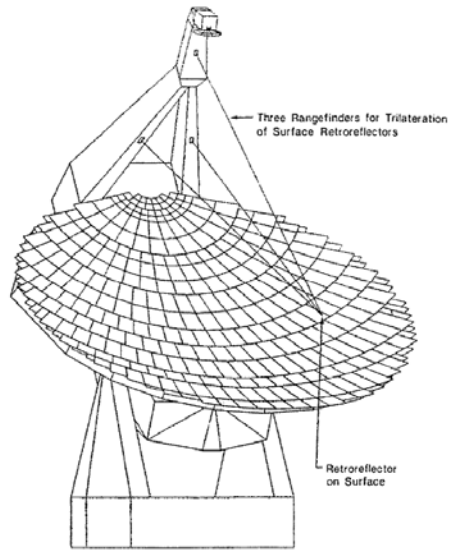
Examples of Metrology Systems

- Amplitude-modulated metrology
  – Application example: SRTM
- Laser heterodyne metrology
  – Application example: SIM

Amplitude Modulated Metrology Sensor

- Ranging accuracy and resolution: mm - um
- Simple and lost cost
  - "Non-interferometric"
  - Light source can be "low coherence", e.g. LED
- Most commercial surveying instruments based on this principle

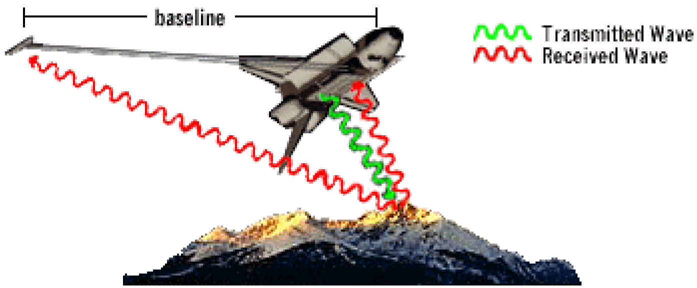




J. M. Payne, D. Parker, and R. F. Bradley, "Rangefinder with fast multiple range capability", *Rev. Sci. Instrum*. 63 (6), pp 3311, June 1992

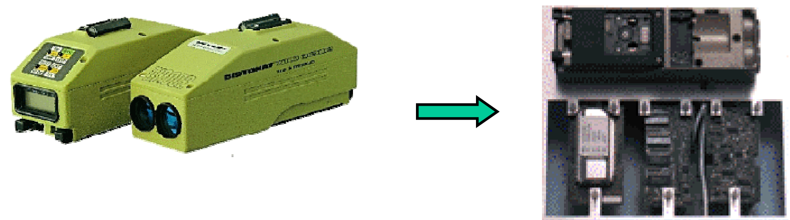
Application Example: SRTM

- Illustration of State of the Art



Radar signals being transmitted and recieved in the SRTM mission (image not to scale).

- Longitudinal (base-line length): modified commercial range finder (inboard)
  - resolution: 0.5 mm
  - Accuracy: 2mm
  - operating range: ~60m
  - retro-reflectors (outboard)

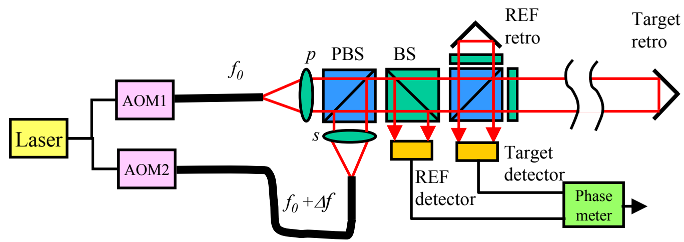


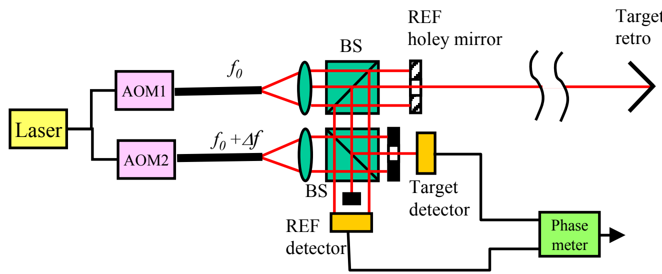
- Lateral:
  - Star tracker inboard
  - 3 LED point source outboard
- Open loop

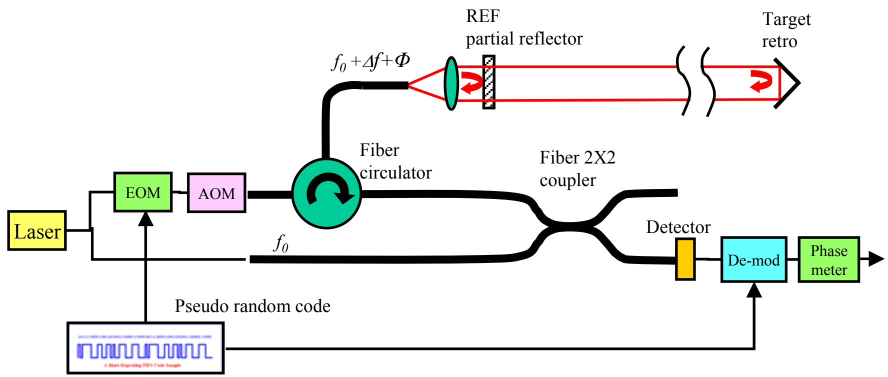
Riley M. Duren and Eldred F.Tubbs , "A Modified Commercial Surveying Instrument For Use as a Spaceborne Rangefinder", *IEEE Aerospace Conference* (2000, Big Sky, Montana)

Laser Interferometric Metrology Sensors

- Want point to point displacement at ~nm to pm resolution
- Use laser heterodyne approach
- Have high bandwidth
  - kHz or higher
  - Low latency
- Good for closed-loop control of high freq jitter
- Three types of interferometers:
  1. Polarization separation
     - N. Bobroff, "Recent advances in displacement measuring interferometry", *Meas. Sci. Technol.*, vol. 4, pp. 907-926, 1993
  2. Spatial separation
     - F. Zhao, "Development of high precision laser heterodyne metrology gauges," *Proc. SPIE*, Vol. 5634, pp. 247-259, 2005.
  3. Temporal separation
     - O. P. Lay, et al, "Coherent range-gated laser displacement metrology with compact optical head", *Opt. Lett*. Vol. 32, No. 20 October 15, 2007





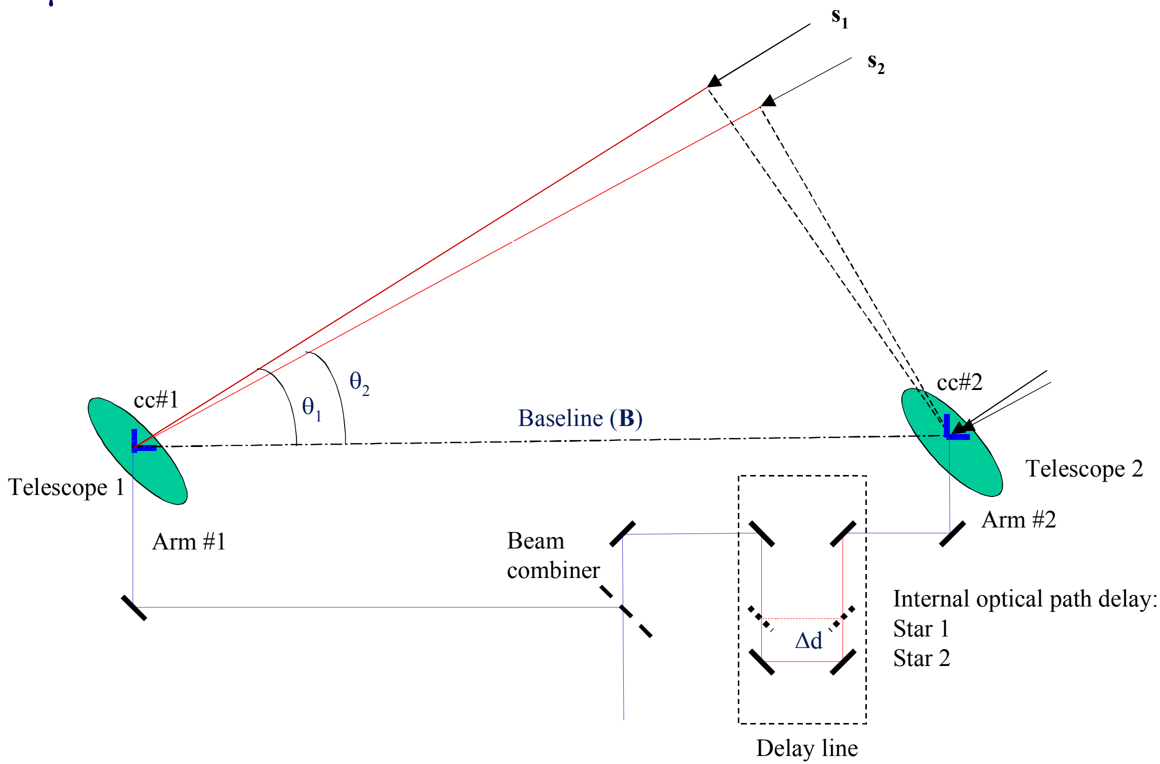


Laser Metrology Gauges in SIM

- SIM model in its simplest form:

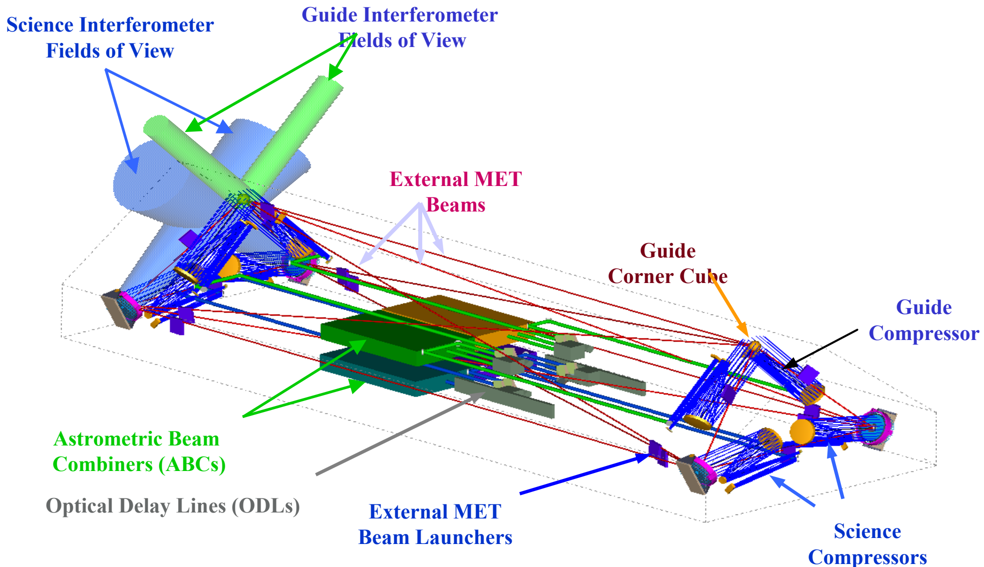
$$\Delta d = \vec{B} \bullet (\vec{s}_1 - \vec{s}_2)$$

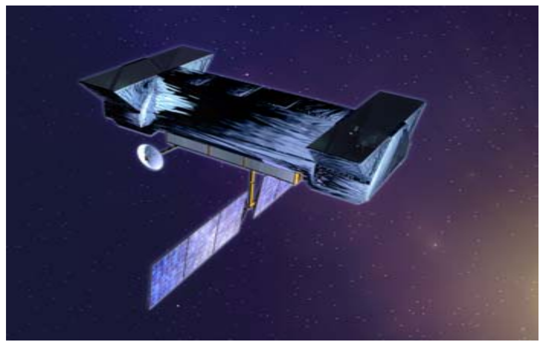
- Laser metrology gauges to measure:
  - Δd (Internal Metrology) – displacement to 3pm RMS
  - **B** (External Metrology) – displacement to 8pm pm RMS and absolute distance to 3μm RMS



State-of-the-art: SIM Laser Metrology

	Internal metrology (Δd)	External metrology (B)
Number of gauges	3 total (1 science, 2 guide)	14 total
Fiducial distance	8m	2.5 – 9m
Range of motion	+/-1.2m (ODL)	~100µm
Velocity	200mm/s while slewing 500µm/s while observing	~1µm/s
Accuracy (absolute)	Not needed	3µm
Accuracy (relative)	3pm (90 s), 45pm (1 hr)	8pm (90 s), 57pm (1 hr)
Telemetry rate	16kHz	1kHz





SIM Technology Challenges

- Picometer knowledge
  - Picometer laser metrology
  - Picometer starlight fringe position measurement
  - Picometer deformation of large (35 cm) optics

- Nanometer control (for dim star fringe sensing)
  - Vibration isolation
  - High bandwidth active optics

Metrology Errors

- Metrology gauge errors:
  - Random noise (error)
  - Systematic error:
    - Diffraction error
    - Cyclic error (periodic nonlinearity)
  - Environmental error (thermal drift)

- Alignment error:
  - Cosine error (pointing);
  - Abbé error (overlap);

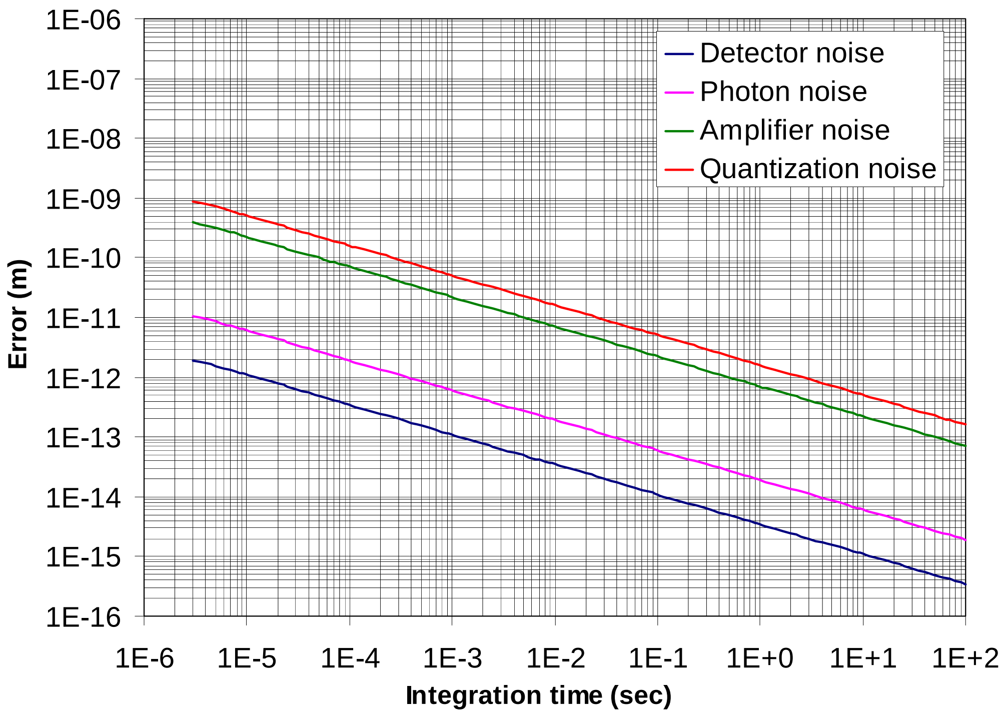
Random Noise Sources

Detector noise	$\varepsilon = \lambda \cdot NEP \cdot \frac{\sqrt{B}}{4\pi\eta P}$
Photon noise	$\varepsilon = \frac{1}{4\pi}\sqrt{\frac{2hc\lambda B}{\eta P}}$
Amplifier noise	$\varepsilon = \frac{\lambda}{2\pi}\frac{\sqrt{4kTRB}}{\eta PR}$
Phase meter quantization noise (zero-crossing)	$\varepsilon = \frac{\lambda}{\sqrt{12}}\frac{f_{het}}{f_{clock}}$

- P=200nW
- NEP=5×10^{-15} W/sqrt(Hz),
- R=100kΩ,
- heterodyne f_{het}=300kHz,
- clock f_{clock}=128MHz,
- bandwidth B=540kHz,

- Use higher laser power
- Use lower heterodyne frequency
- Use longer integration time (averaging)

$$\langle \delta x \rangle = \frac{\varepsilon}{\sqrt{N}} = \frac{\varepsilon}{\sqrt{f_h \tau}}$$



Systematic Error (1) -- Diffraction

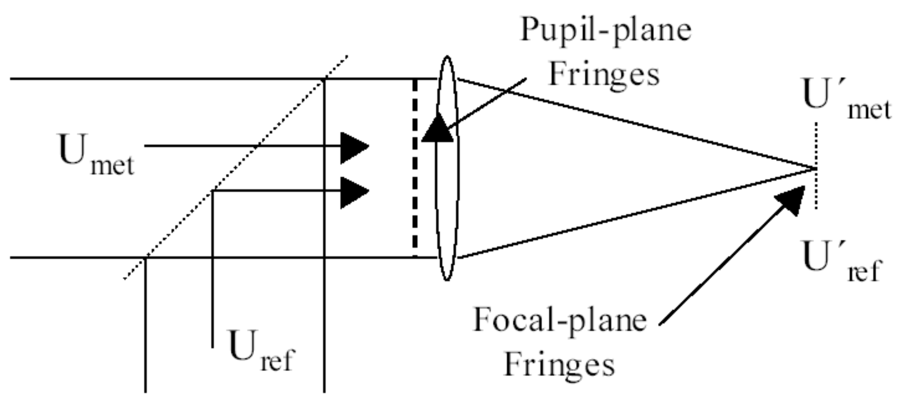
- Geometric path length ≠ average phase
  - Due to beam diffraction

- Fresnel (paraxial) approximation

$$U(x,y;z)=\frac{exp(ikz)}{i\lambda z}\int\int_{-\infty}^{\infty}U_1(x_1,y_1)exp\left\{i\frac{k}{2z}\left[(x-x_1)^2+(y-y_1)^2\right]\right\}dx_1dy_1$$

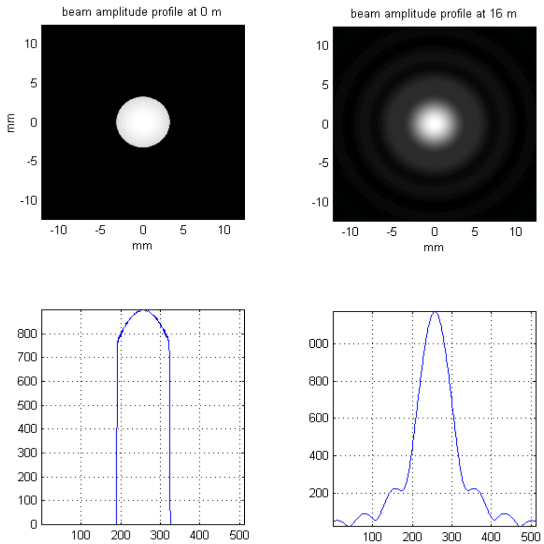
- Average phase

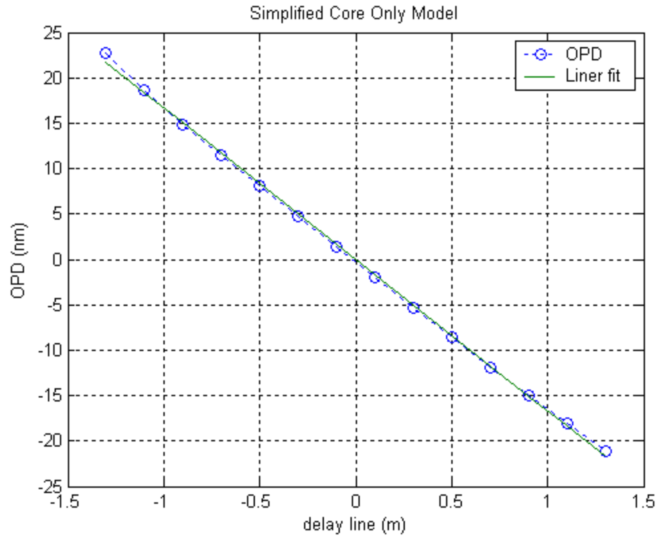
$$[\phi]_{av}=arg\left[\iint_{det}U_{met}(x,y)U^*_{ref}(x,y)dxdy\right]$$

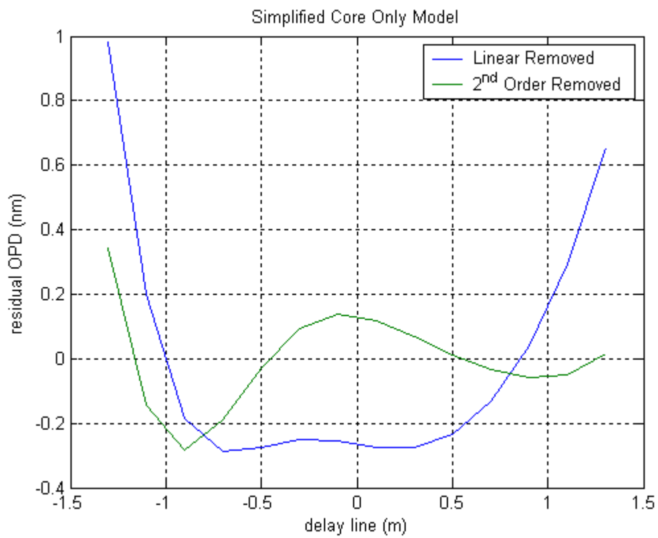


Systematic Error (1) – Diffraction (cont'd)

- Apply diffraction correction (calibration) based on model calculation
- Example: truncated Gaussian

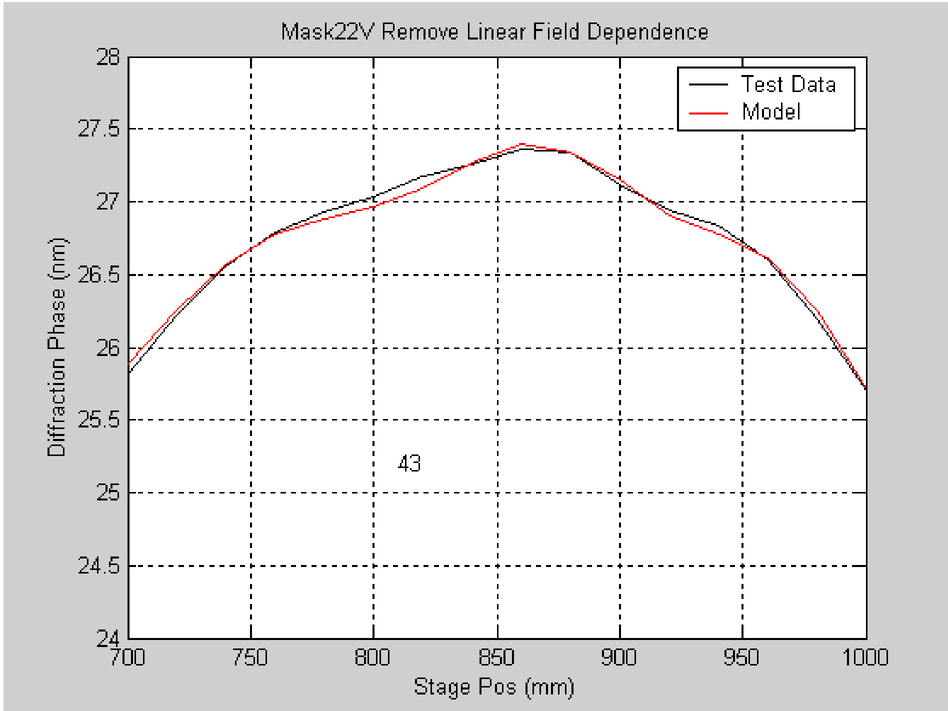






Systematic Error (1) – Diffraction (cont'd)

- Successfully used in several ground testbed demonstrations (MAM, DTB)



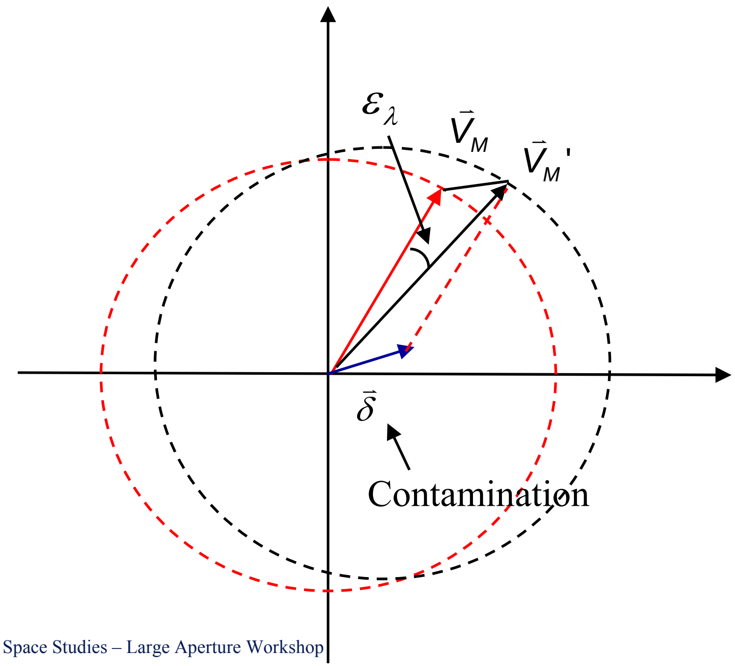
D. B. Schaecter, et al, "Diffraction hardware testbed and model validation," *Proc. SPIE* vol.4852, pp. 302-314, 2002.

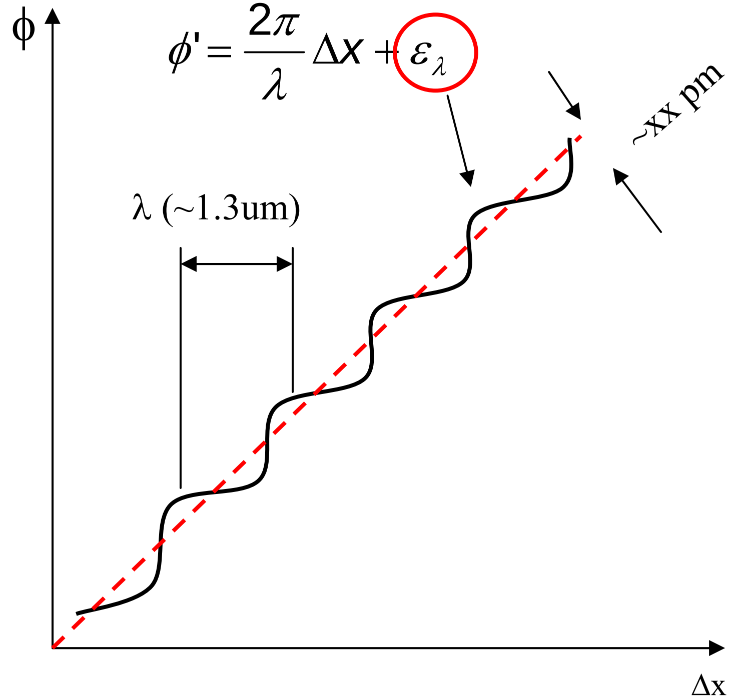
Systematic Error (2) –Cyclic Error

- Defined as "periodic (λ) nonlinearity" between measured phase and actual displacement
- Caused by "contamination" to the heterodyne signals

$$V_M' = V_M \sin\left(2\pi f_h t + \frac{2\pi}{\lambda}\Delta x\right) + \delta \sin(2\pi f_h t + \phi_1)$$

$$\vec{V}_M' = \vec{V}_M + \vec{\delta}$$



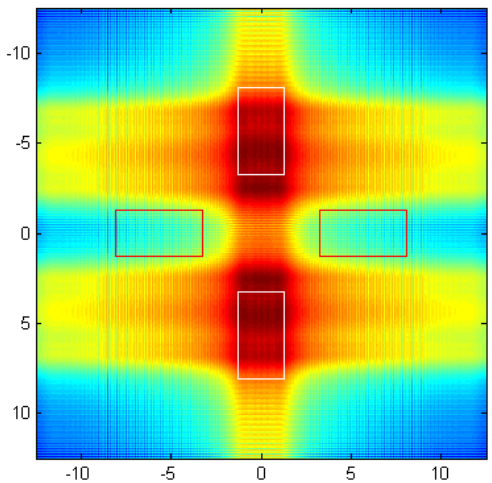


Systematic Error (2) –Cyclic Error

Cyclic error:

$$\varepsilon_\lambda = \frac{\lambda}{2\pi}\sqrt{\frac{P_{xtalk}}{P_{signal}}}$$

For example:
-90dB cross-talk results in 6.5pm



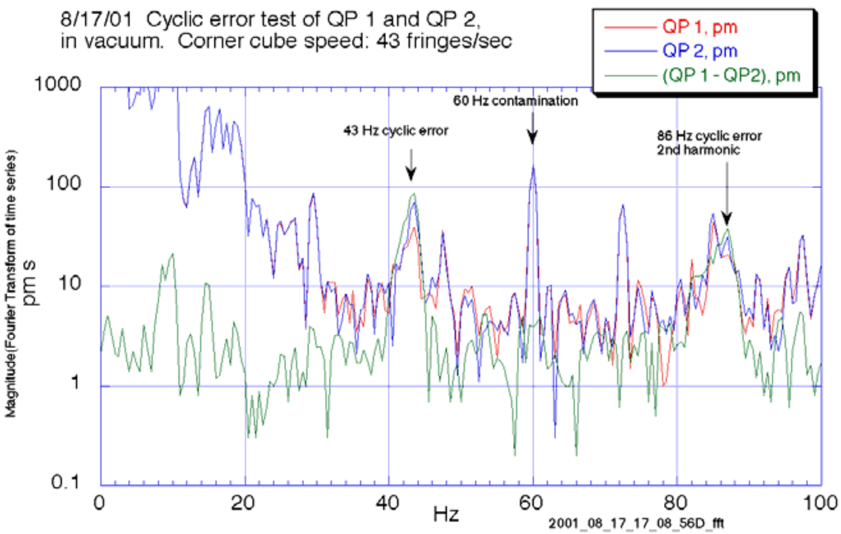
Mask patterns to minimize diffraction cross-talk

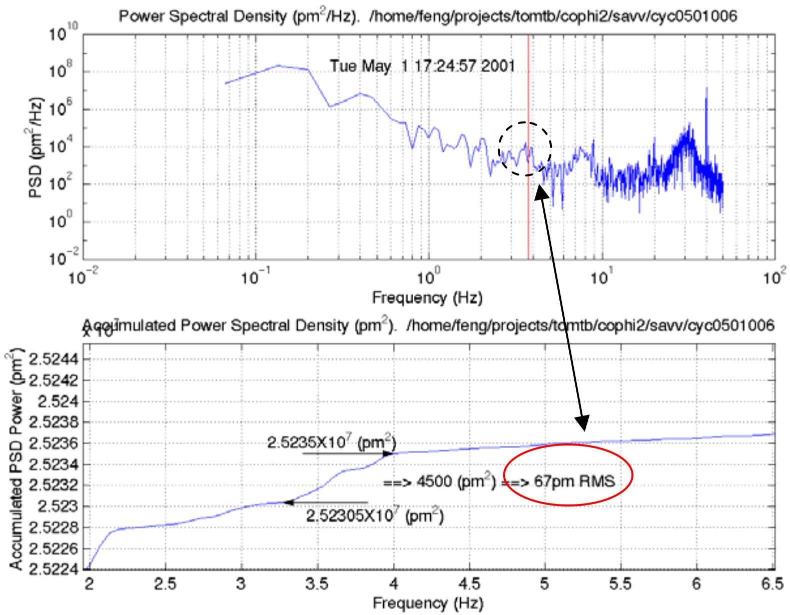
Common sources of cyclic error:

- Optical cross-talk:
  - Diffraction
  - Ghost reflections
  - Scattering
  - Polarization leakage (commercial DMI)
- Electrical cross-talk
  - EMI in AOM RF drivers
  - EMI between MEAS and REF signals
  - Ground coupling

F. Zhao, et al, "SIM internal metrology beam launcher development," *Proc. SPIE* vol.4852, pp. 370-379, 2002.

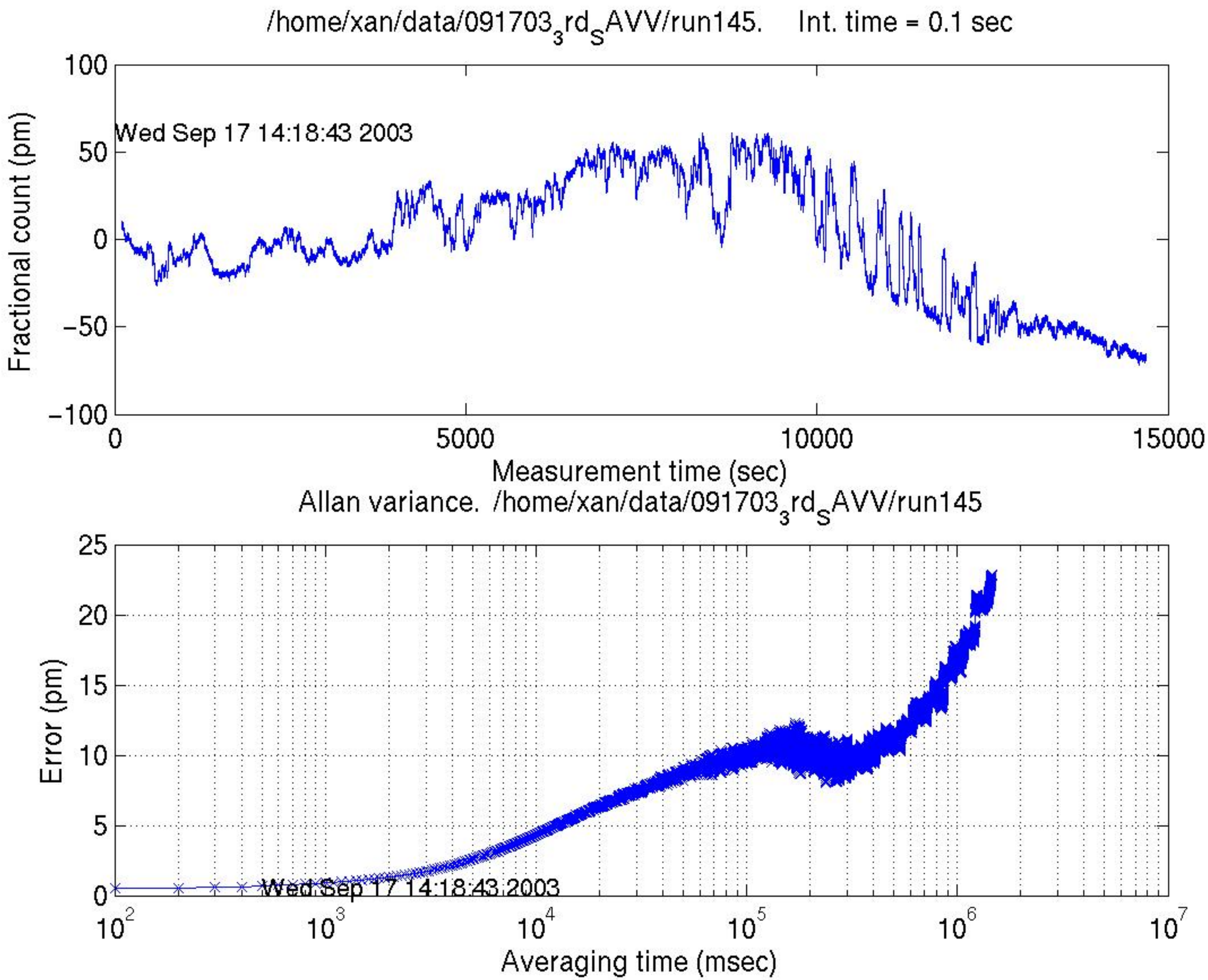
Cyclic Error Results





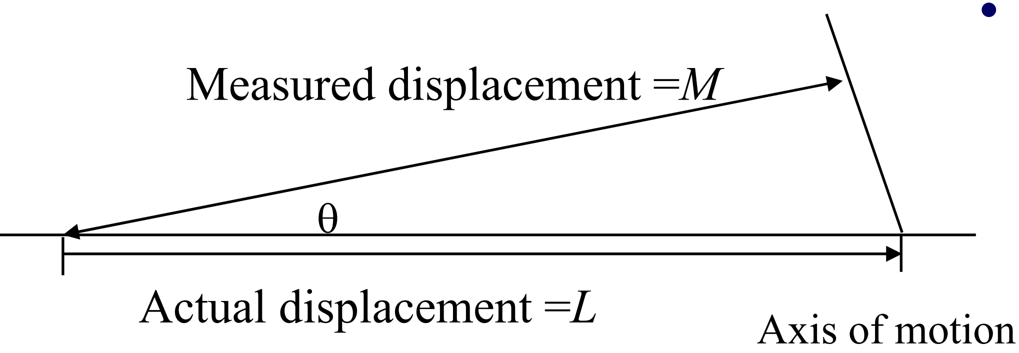
QP2	QP3	QP8	QP12	QP16	SAVV	Milestone #1
44	16	45	28	29	67	100 (pm, RMS)

Environmental Errors – SAVV Beam Launchers



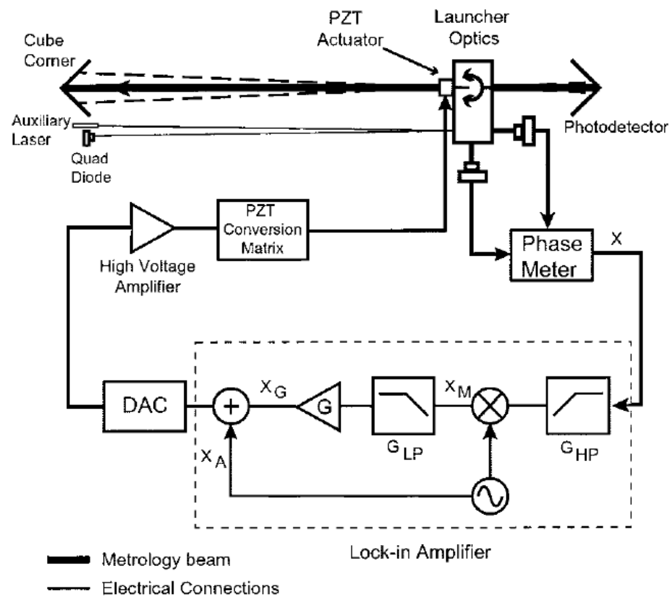
Pointing error- Cosine Error

- Measurement along a non-parallel axis



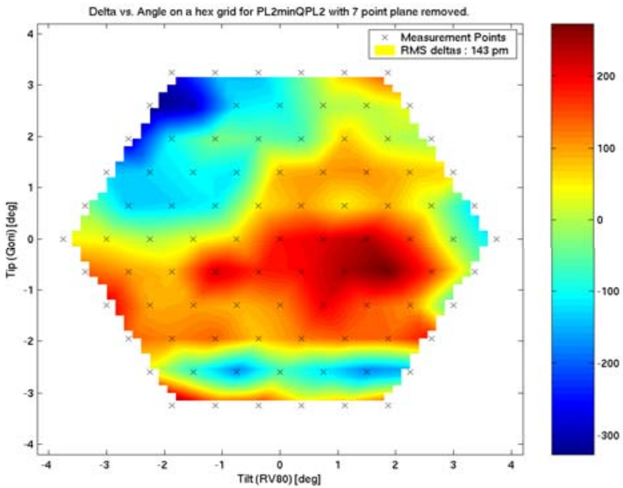
$$\varepsilon = L - M = L(1 - \cos\theta) \approx \frac{1}{2} L \theta^2$$

- Solution: dither in laser beam pointing, lock to minimum optical path length
- Demonstrated ~0.5urad pointing accuracy in SIM

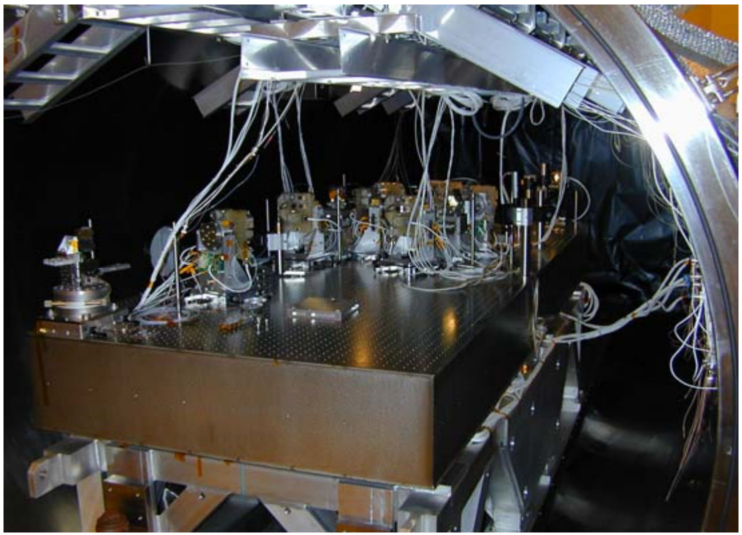


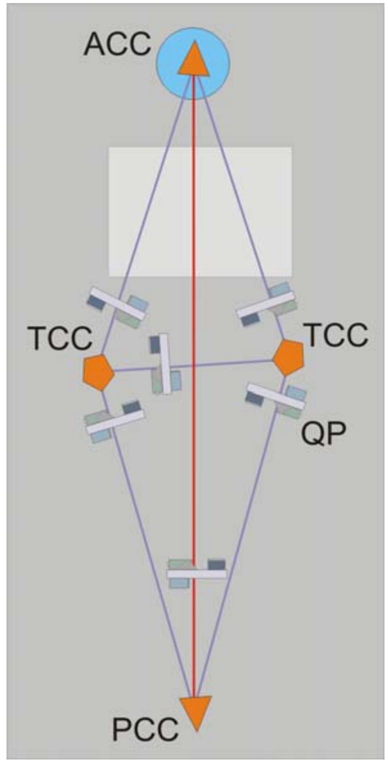
Logan, J.A., et al, "Automatic Alignment of a Displacement-measuring Heterodyne Interferometer," Appl. Opt., 41, p. 4316 (2002)

Metrology Truss: Kite Testbed



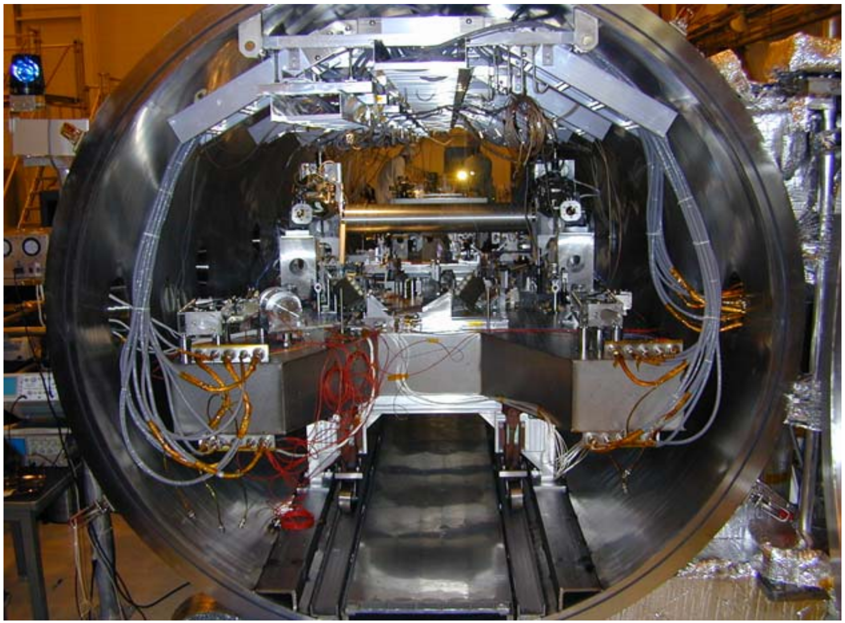
Narrow Angle (90% conf.)	[pm]
SIM Goal	8
Without optical averaging	23
With optical averaging	11

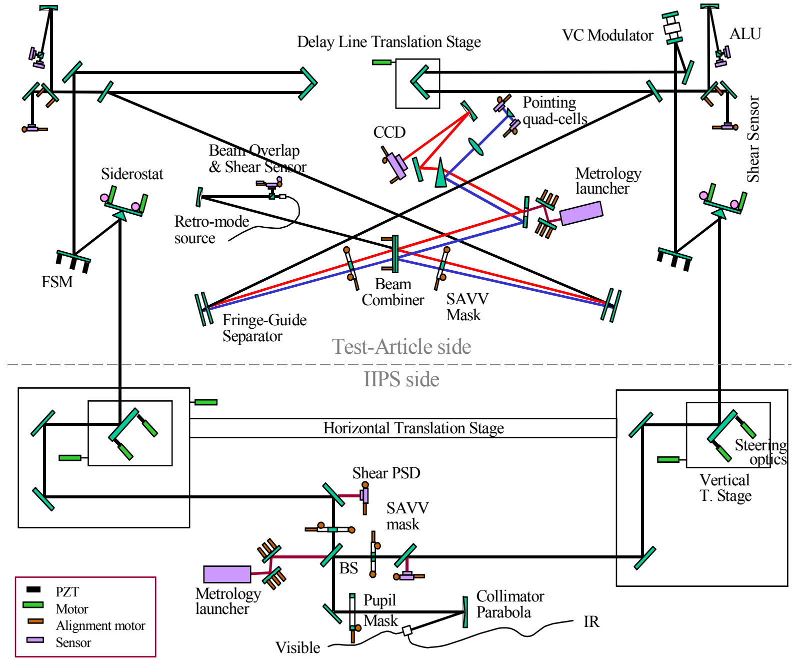




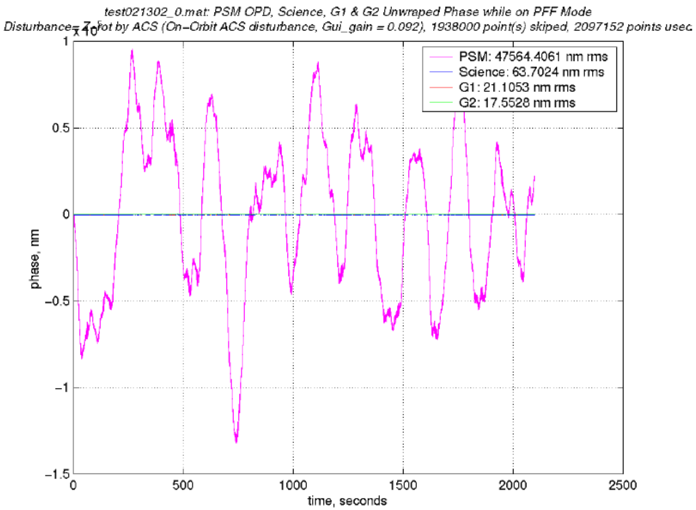
Interferometer: MAM Testbed

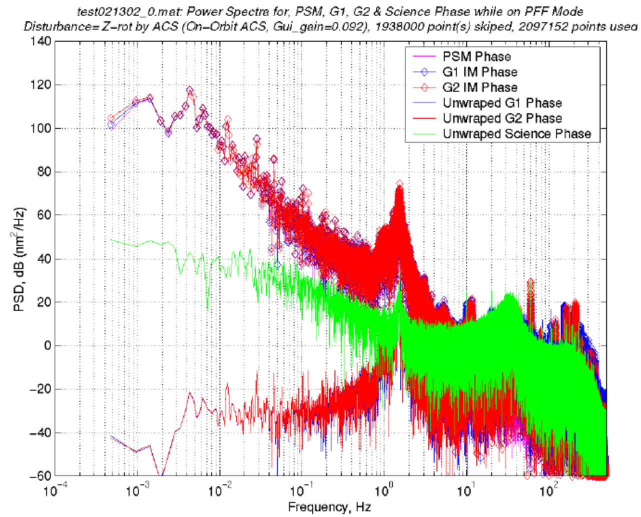
Narrow Angle Requirements				
MAM	Goal	Baseline		Testbed
Astrometry	1.1	3.0	uas	Results
FD	17.9	99.0	pm	
FI	16.0	38.0	pm	13.7

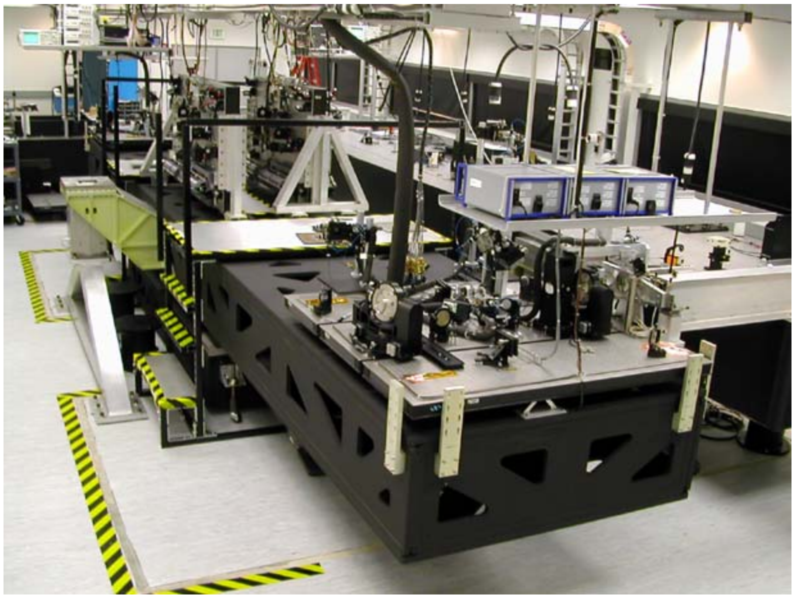




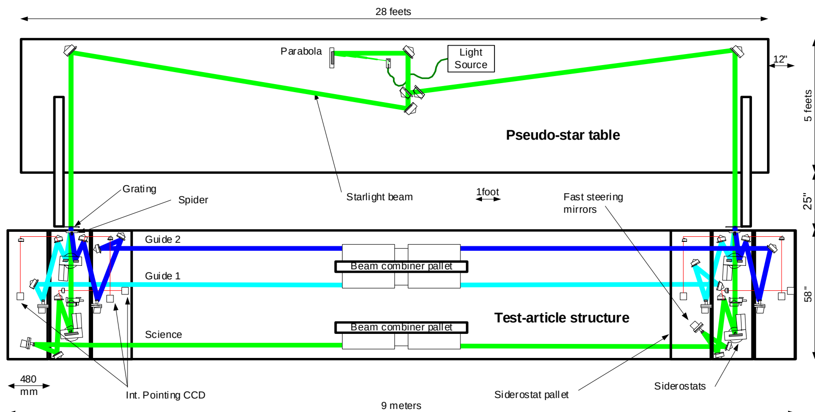
System Testbed 3 –STB3







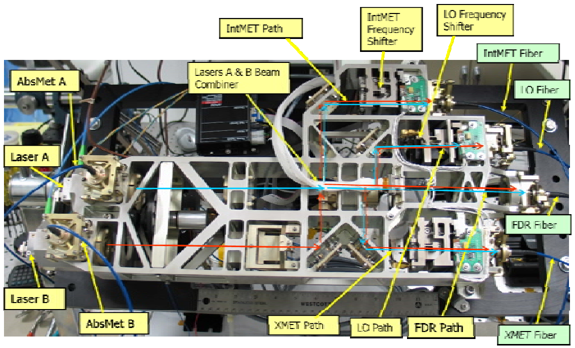
Starlight system optical layout - phase 2



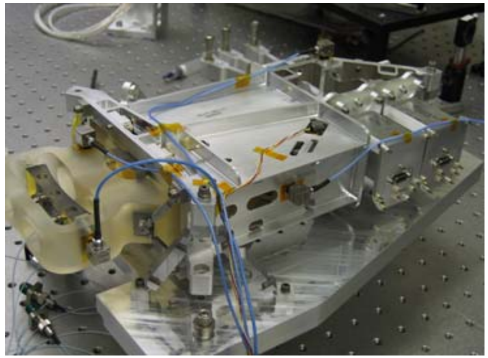
A Glance of SIM Metrology Hardware

Performance demonstrated after environmental tests (random vibe, thermal vac)

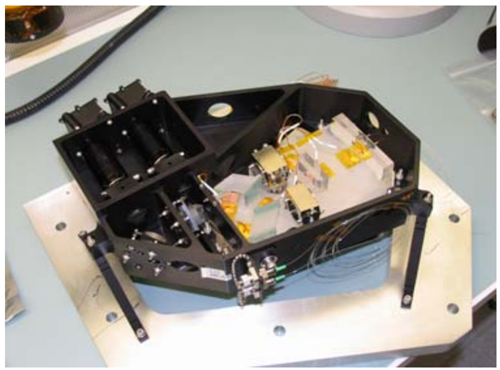
Metrology source brassboard

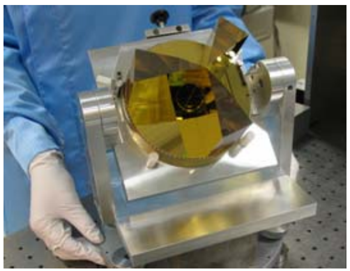


External beam launcher brassboard

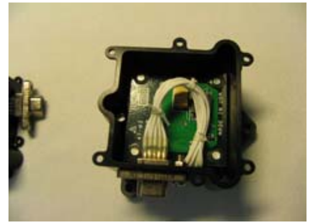


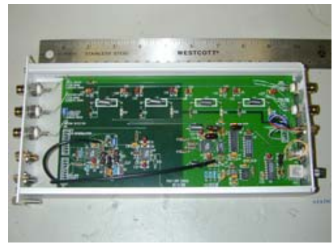
Internal beam launcher brassboard

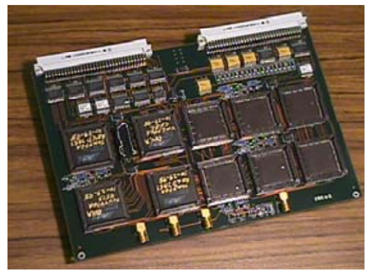




Metrology fiducials







Phase meter electronics

Summary

- Metrology performance ranging from mm to pm
- Various technical maturity
  - Sub-millimeter flight technology demonstration example SRTM
  - Nanometer and picometer component technology development is complete -- all components have achieved TRL-5 (SIM)
  - Nanometer closed-loop control system demonstration is complete -- at TRL-6 (SIM)
  - Picometer sensing at system level demonstration is completed -- TRL-6 (SIM)
- Design tools (such as diffraction code), test/diagnostic tools established