LASER METROLOGY SENSING AND CONTROL FOR LARGE SEGMENTED-MIRROR TELESCOPES

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Outline

- Introduction
- Optical hexapod
- Swept-frequency laser metrology
  - Absolute optical pathlength measurement
  - Relative optical pathlength measurement
- Discussion

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Background

- Wavefront sensing and control for large segmented telescopes always a challenge (both technically and financially)
- Edge sensors have been successfully used in some large segmented systems such as Keck, HET, SALT, etc.
  - Draw back of edge sensors include:
    - M1 – M2 distance not measured
    - M1 global curvature not measured
    - Limited control bandwidth due to computational complexity
- This paper describes a laser metrology system that could be used for segmented mirror telescope control

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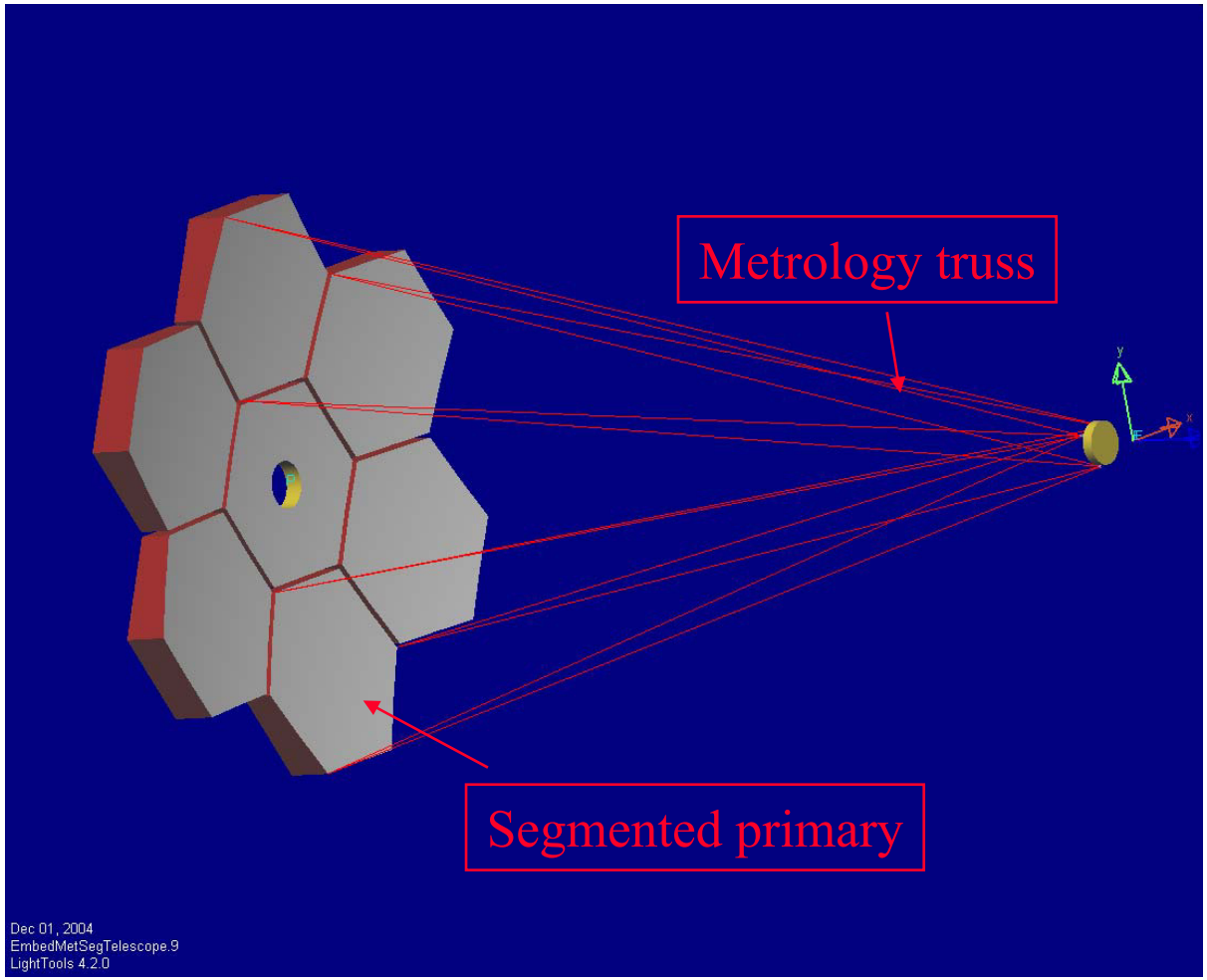
Laser Metrology in Segmented Telescopes

- Use of laser metrology truss to tie all the segments together with a common reference such as M2
- Optical hexapod 6DOF (tripod 3DOF) for segmented telescopes



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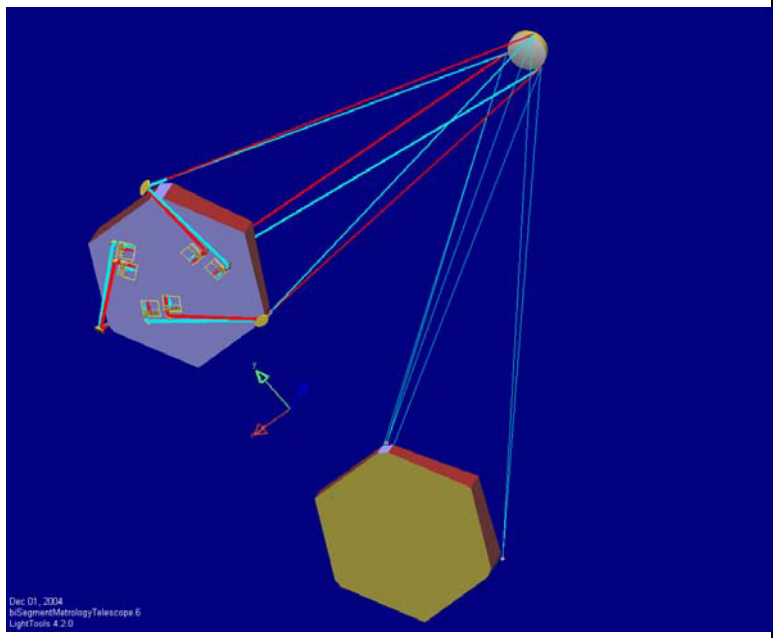
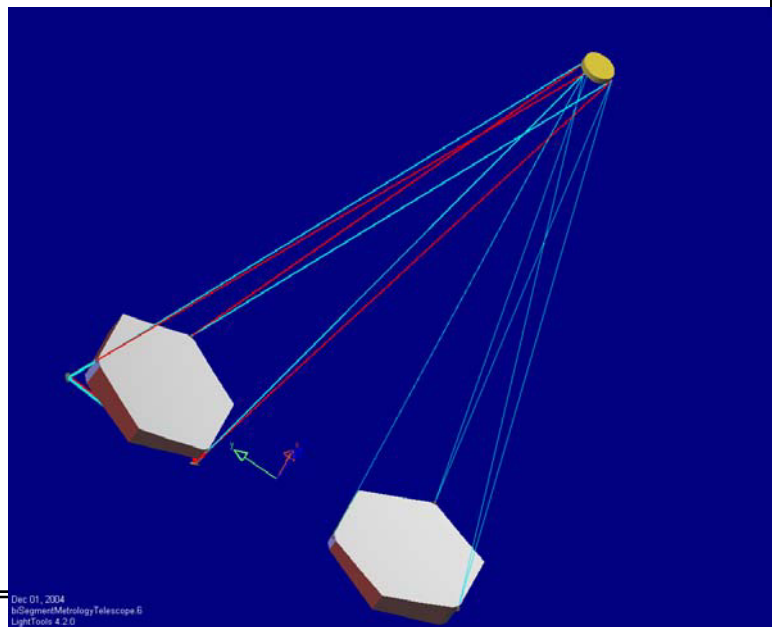
Optical Hexapod (OHP) Concept

- Six (6) laser beams between two rigid panels (M1 and M2)
- Three reference points on each rigid panels
- All 6 DOF between two panels are measured





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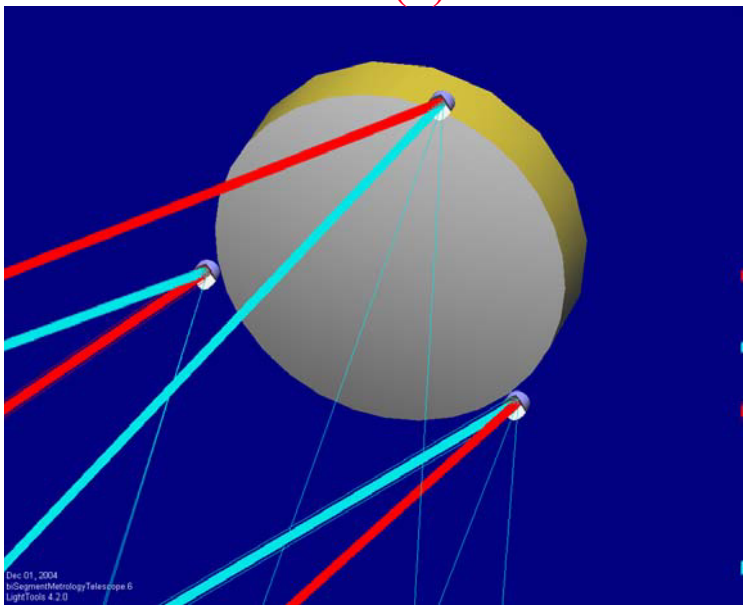
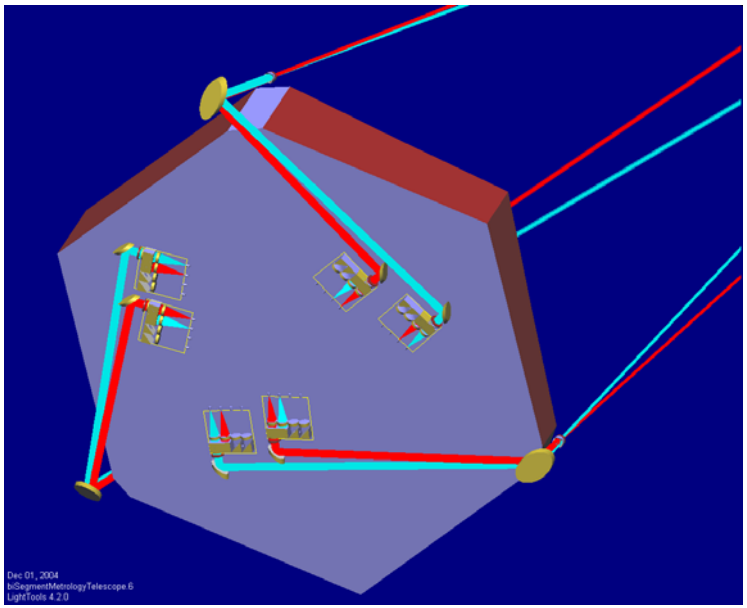
Optical Hexapod (OHP) Concept

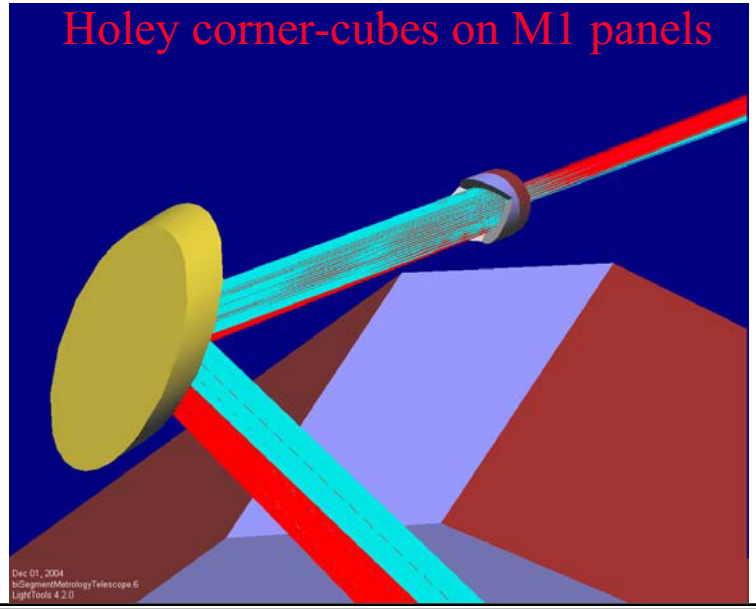
Common fiducials (3) on M2



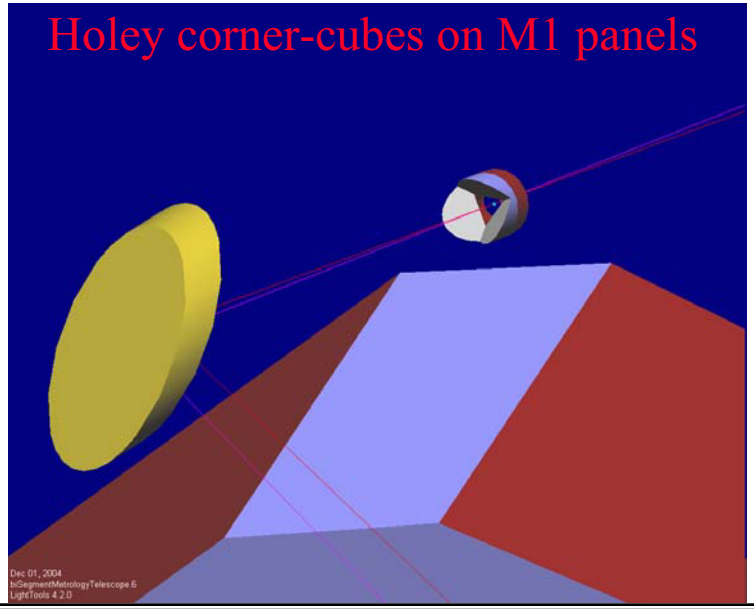
M1 panels with embedded beam launchers



Holey corner-cubes on M1 panels



Holey corner-cubes on M1 panels



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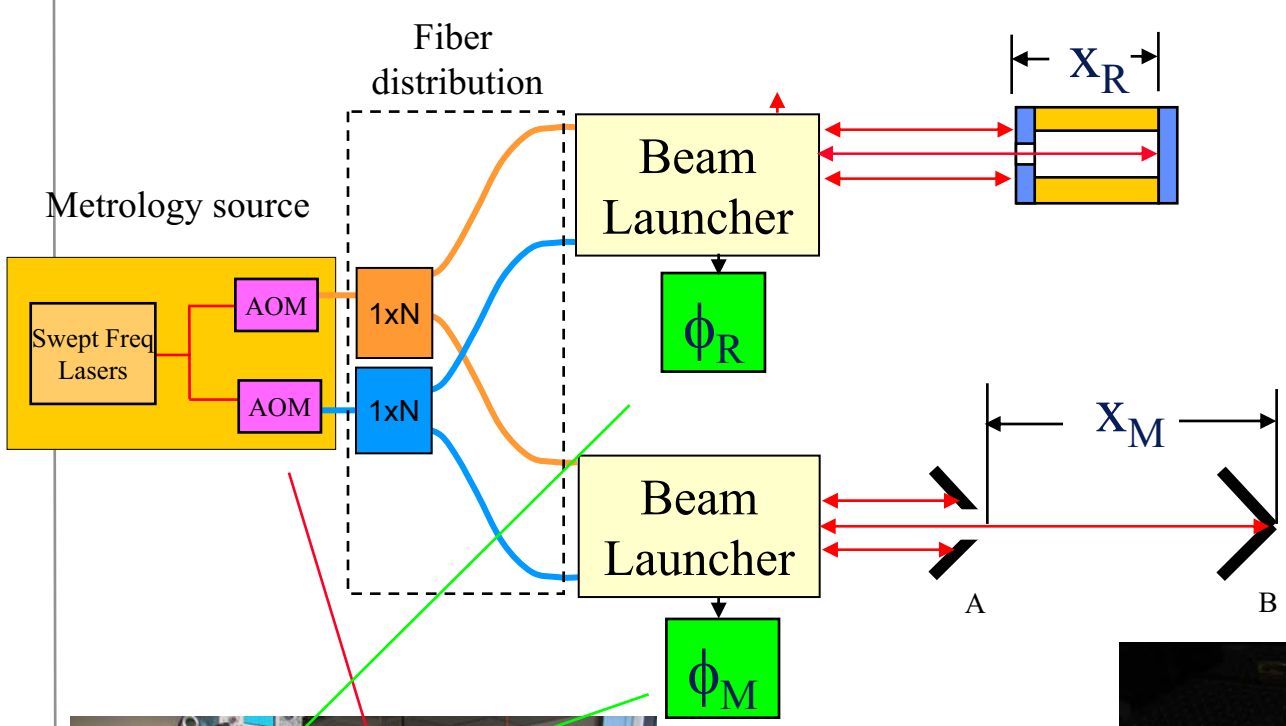
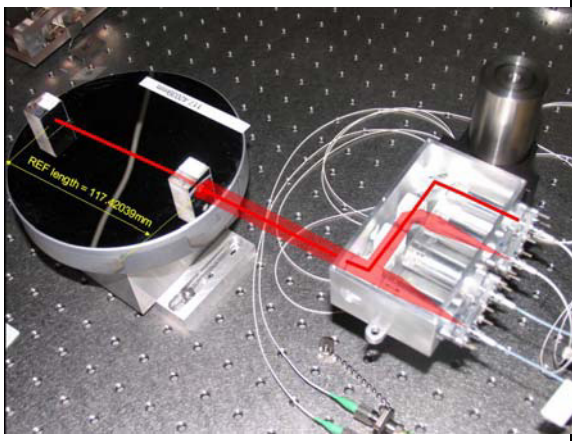
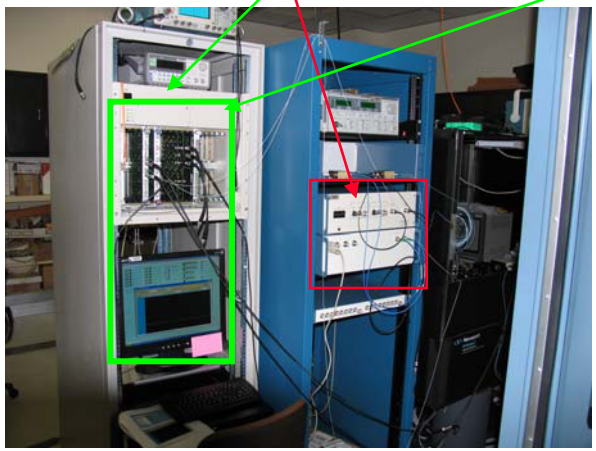
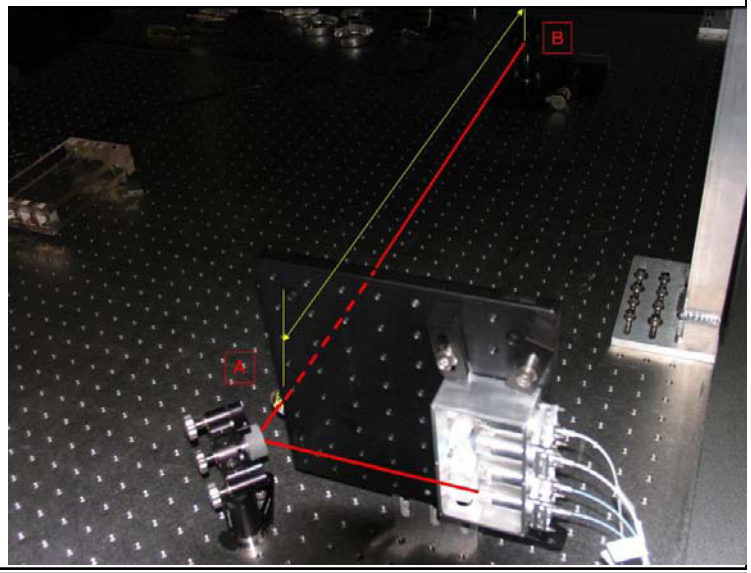
Swept-frequency laser metrology

REF beam launcher with a calibrated REF cavity









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Swept Frequency Absolute Ranging

- Phase from a COPHI beam launcher

$$\phi = \phi_1 - \phi_2 = \frac{4\pi}{\lambda} x = \frac{4\pi}{c} f_o x$$

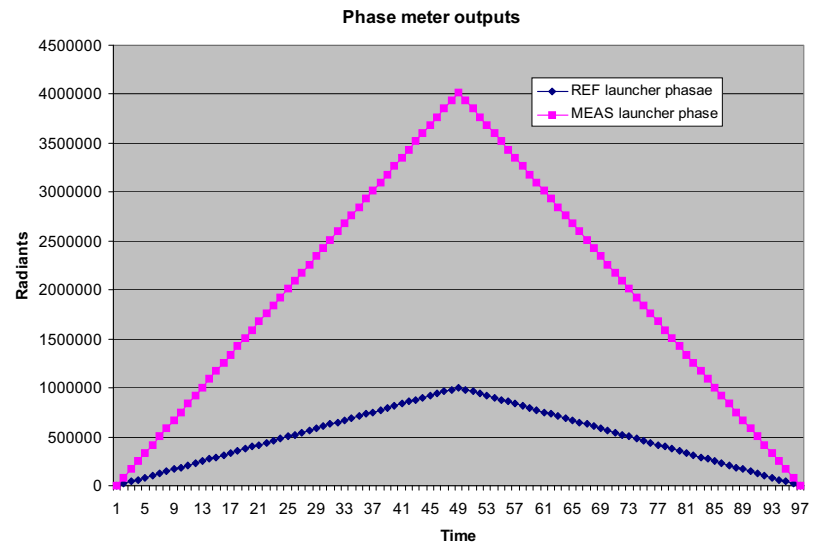
- Swept the laser frequency (Δf_o)
- Measure phase changes in both MEAS and REF beam launchers

$$\begin{cases} \Delta\phi_M = \dfrac{4\pi}{c} x_M \Delta f_o \\ \Delta\phi_R = \dfrac{4\pi}{c} x_R \Delta f_o \end{cases}$$

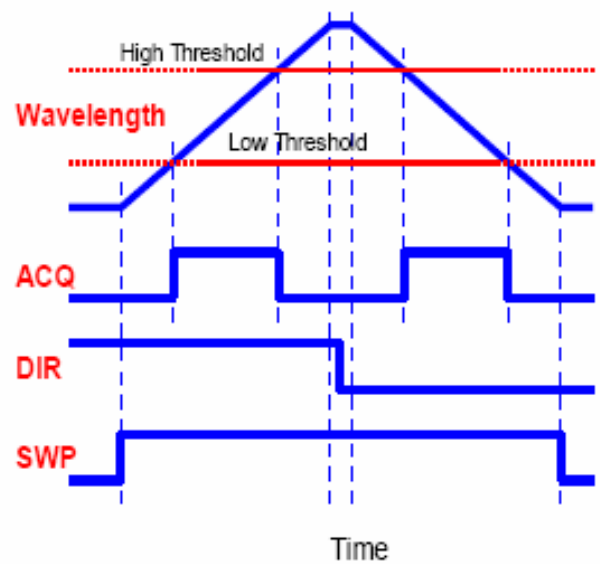
- Calculate MEAS distance:

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

- Least-square fit to achieve high accuracy



Interface Timing (full sweep)



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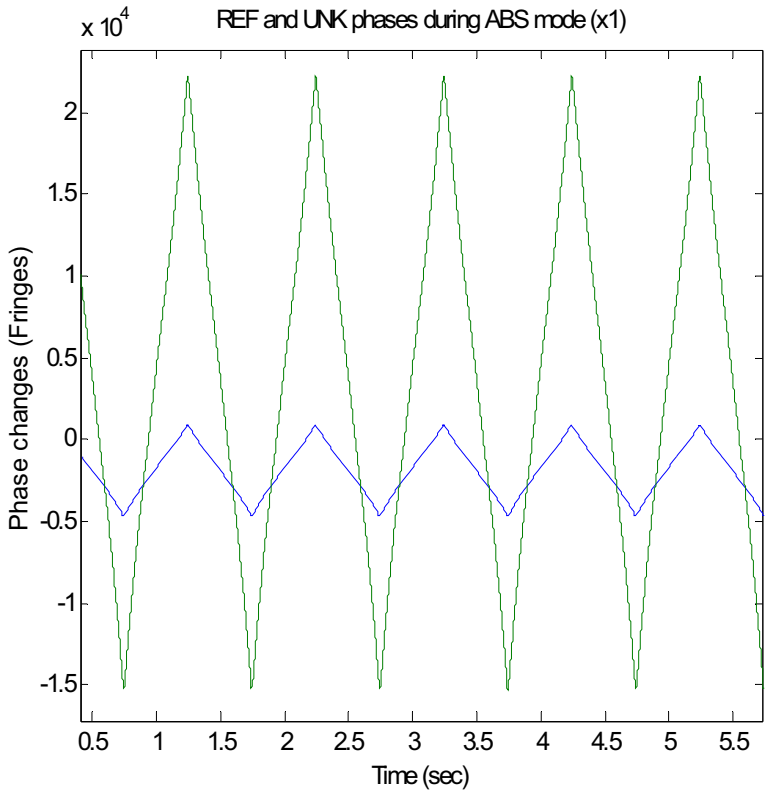
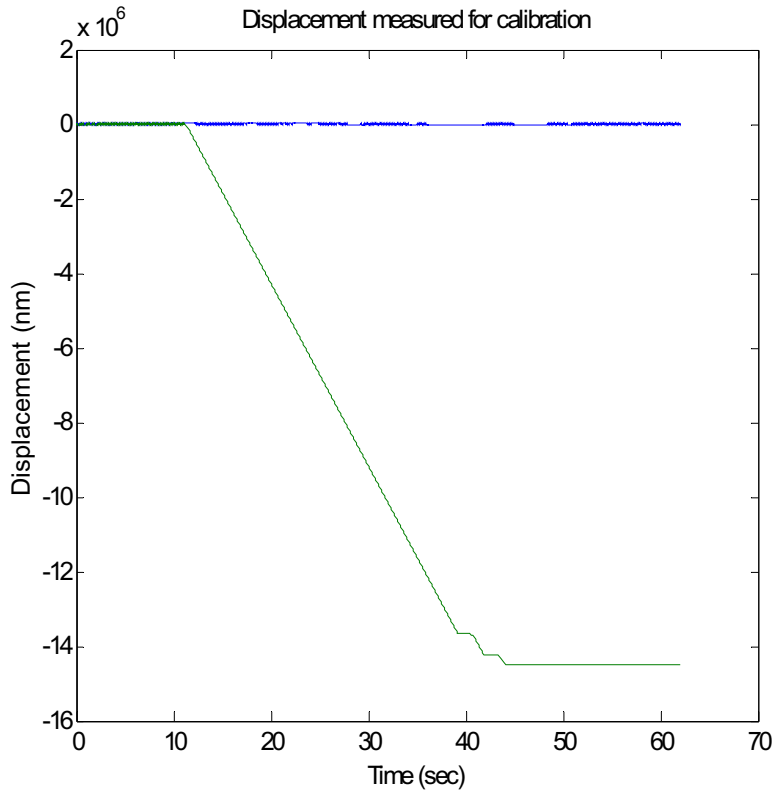
Phase Measurement – Abs and Rel Modes

Absolute Mode



Relative Mode



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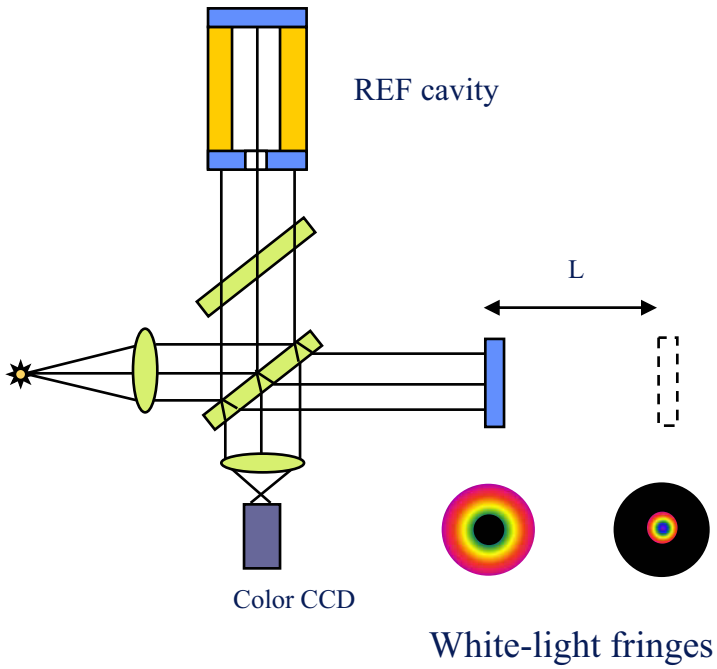
REF Cavity Calibration – Method #1

- Use white-light Michelson interferometer:
  - REF cavity in one arm
  - Mirror on translation stage in the other arm
  - Measure displacement of the mirror between two white-light fringes
    - Optical encoder ~1um
    - DMI ~3nm
- REF cavity thermal stability: ~0.01ppm/C° (ULE material)



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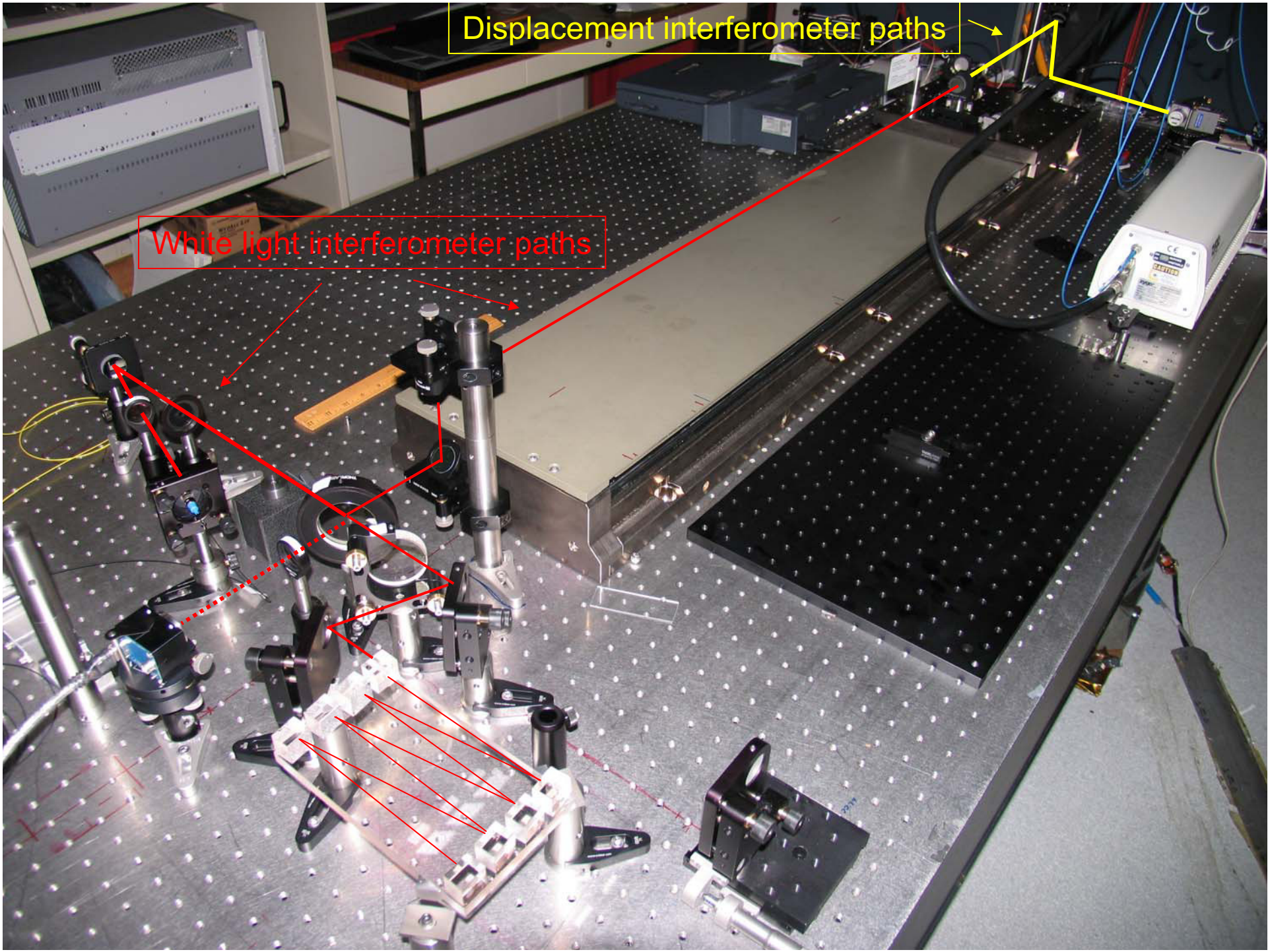
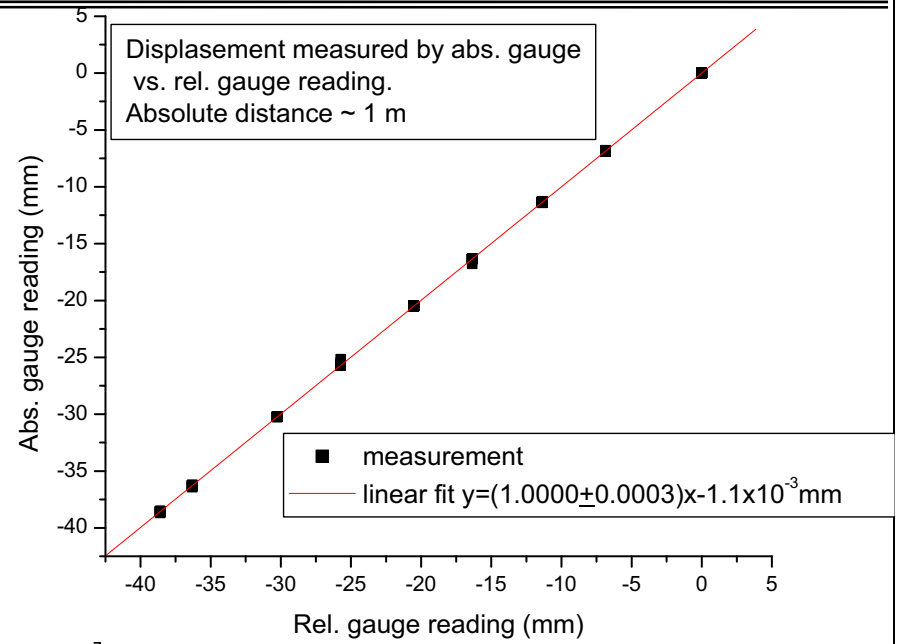
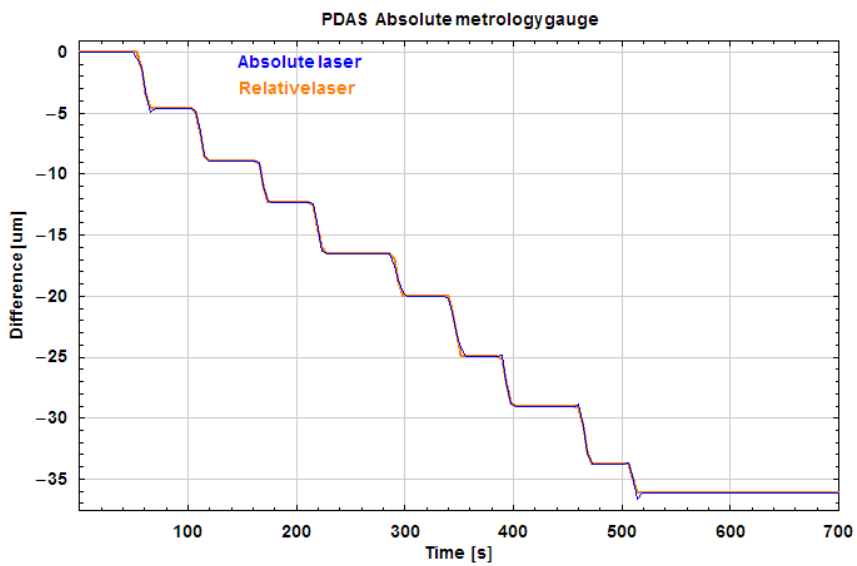

Displacement interferometer paths
White light interferometer paths

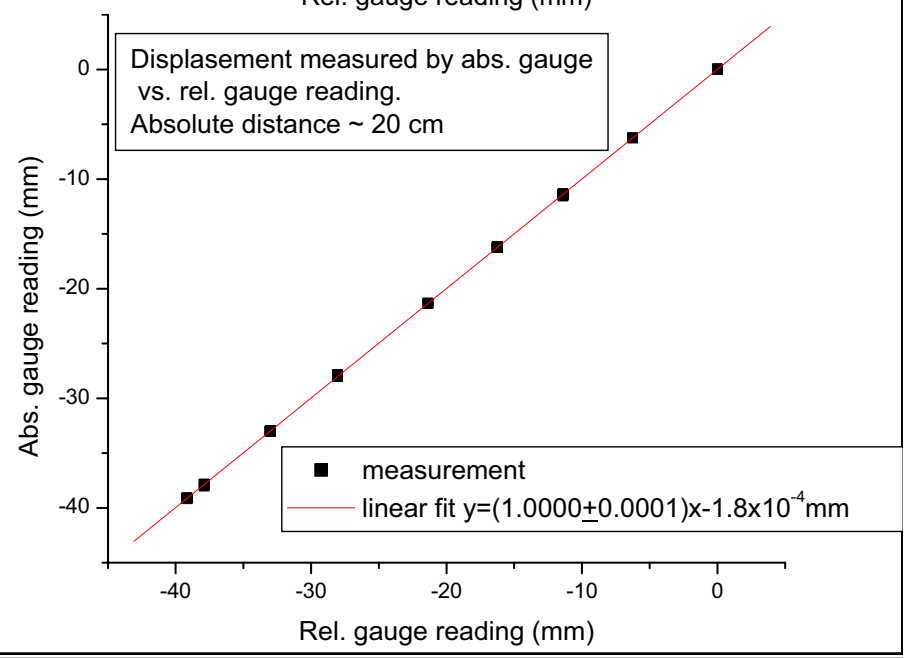
Initial Performance

Absolute pathlength ~ 1-3 um over 1m distance

REF cavity length calibration requires improvement and independent verification







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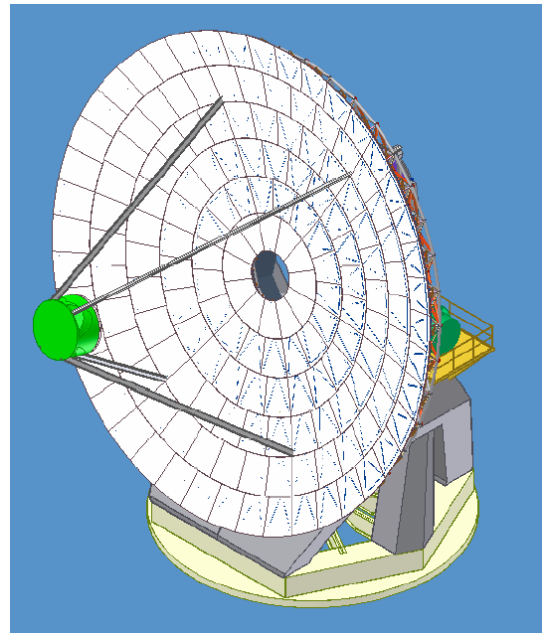
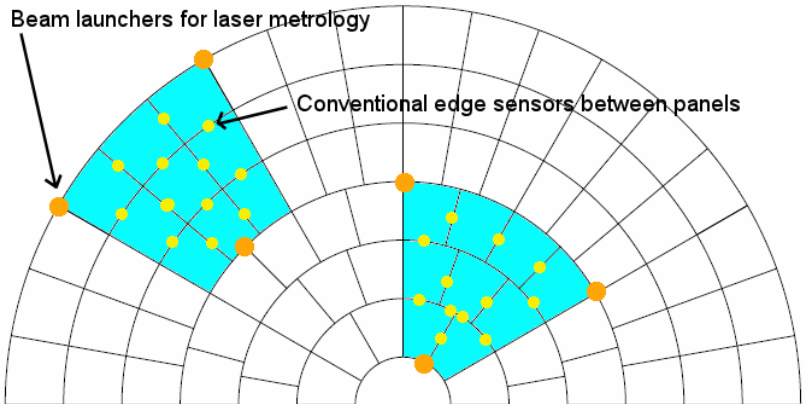
Can laser metrology be useful in ground-based telescopes?

- Laser metrology and edge sensors to actively align and control the telescope:
  - Primary mirror surface figure
  - Distance between primary and secondary mirrors





Performance Goals

Aperture	25	m
Wavelength	200–1500	μm
Field of view	20′	
Pointing	0.35″	
Surface (rms), active	10	μm
Primary focal ratio	0.6	
Naysmyth focal ratio	8	
Site altitude	> 5000	m
Water vapor (median)	< 1	mm

Project Plan

Cornell Caltech agreement	2004 q1
Project office established	2004 q4
Feasibility study	2004-2005
Feasibility study review	2006 q1
Engineering development	2006-2007
Construction start	2008
Telescope complete	2012

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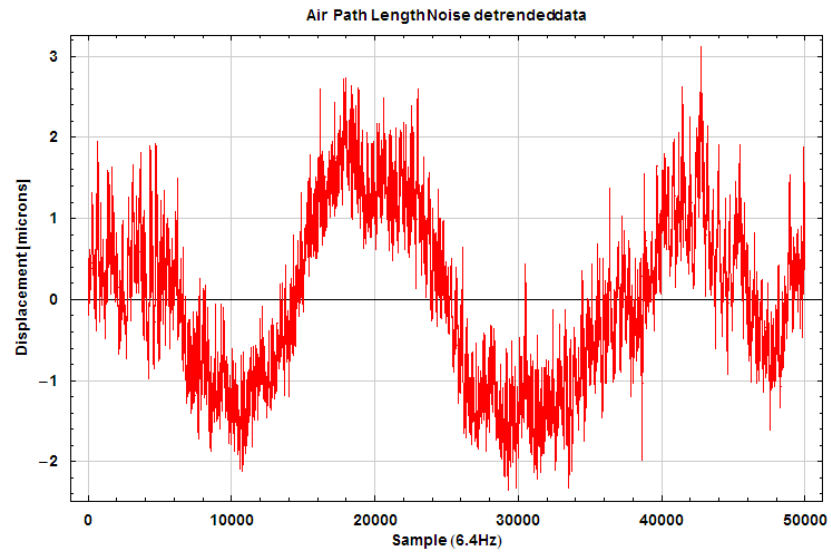
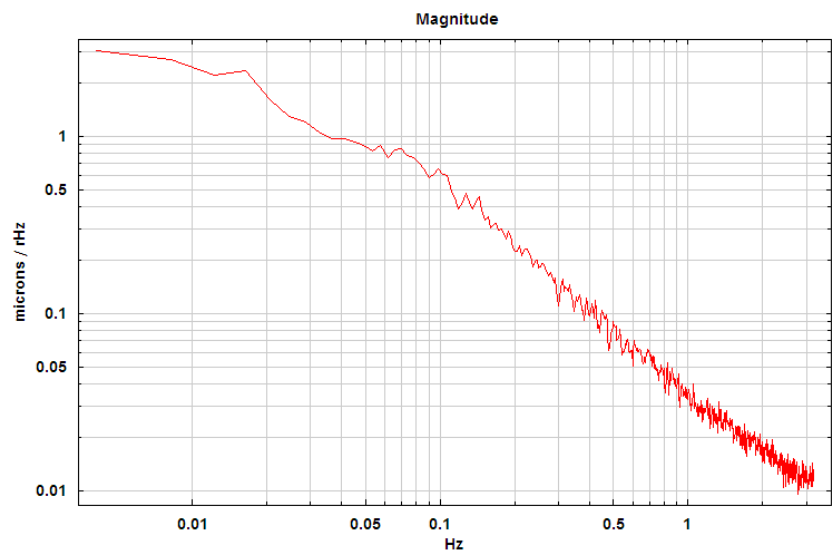
Measurement in the lab with open air

- 80 ft long open optical path
- Optical table with folded mirrors
- Ambient temperature (21C+/-1C)
- Relative humidity (43%).
- CTE of optical table ~10^{-5} ➔ 270μm/°C
- Index of air (i.e. optical path length) also depends on environment:

$$n = 1 + 7.86 \cdot 10^{-4}\, p/(273+t) - 1.5 \cdot 10^{-11}\, RH\,(t^2 + 160)$$

- Turbulence is an important factor for dynamic sensing and control
- Needs more study





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Summary

- Described an optical hexapod metrology concept
  - Can work together with edge sensors
  - Can measure M1 – M2 distance and M1 global curvature
- Swept-frequency laser metrology system
  - Absolute optical path length measurement (~1um)
  - Relative optical path length measurement (~nm)
- Air turbulence is a concern for ground-based telescopes and needs further study

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Backup slides

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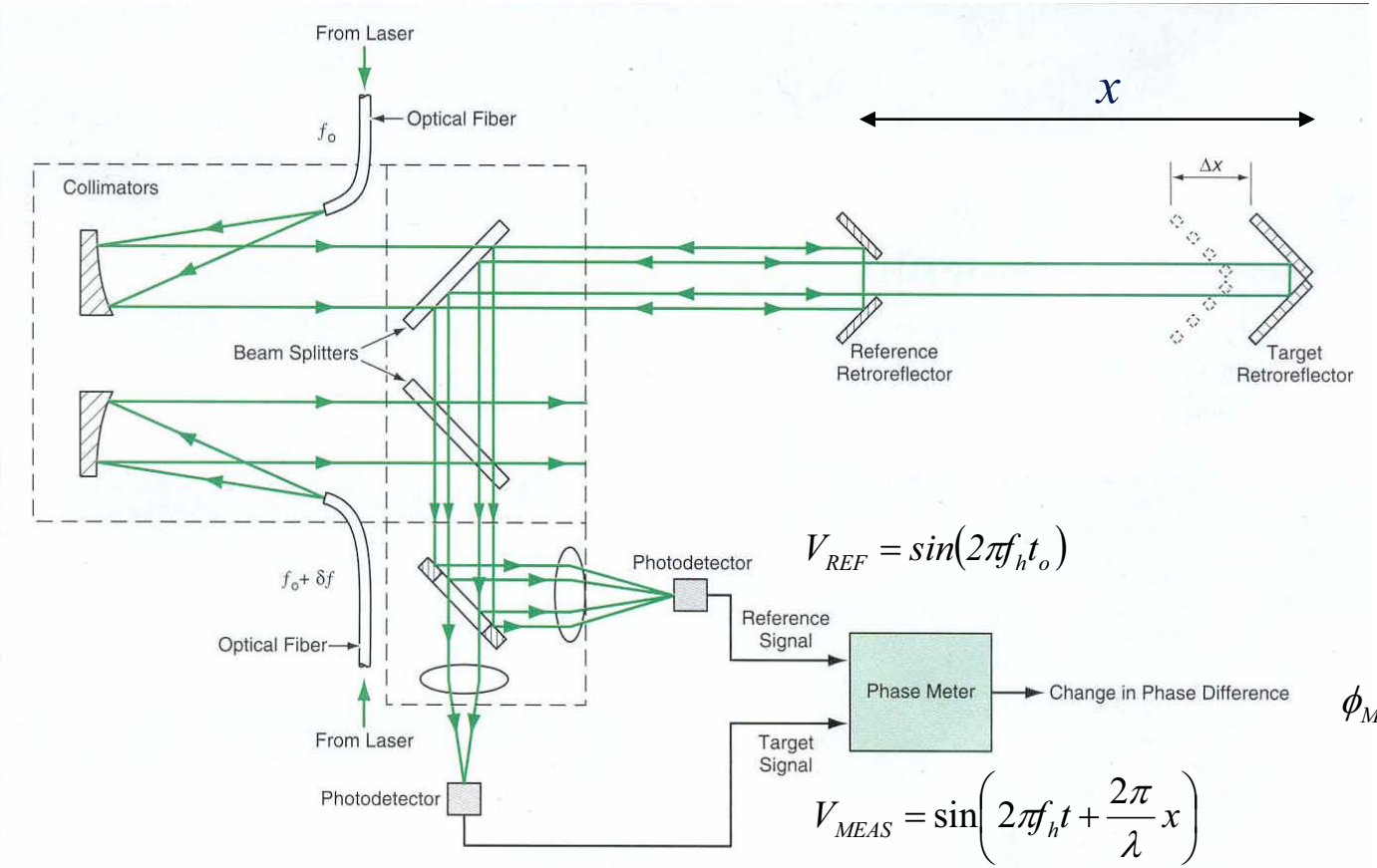
Common Path Heterodyne Interferometer (*COPHI*)

- Measurement and reference signals from spatially separated different parts of the same wavefront
  - Reduced optical cross-talk
  - Improve thermal stability (common path)
  - Variety of configurations for different types of measurements



$$V_{REF} = sin(2\pi f_h t_o)$$

$$V_{MEAS} = \sin\left(2\pi f_h t + \frac{2\pi}{\lambda} x\right)$$

$$\phi_{MEAS} - \phi_{REF} = \frac{2\pi}{\lambda} x$$

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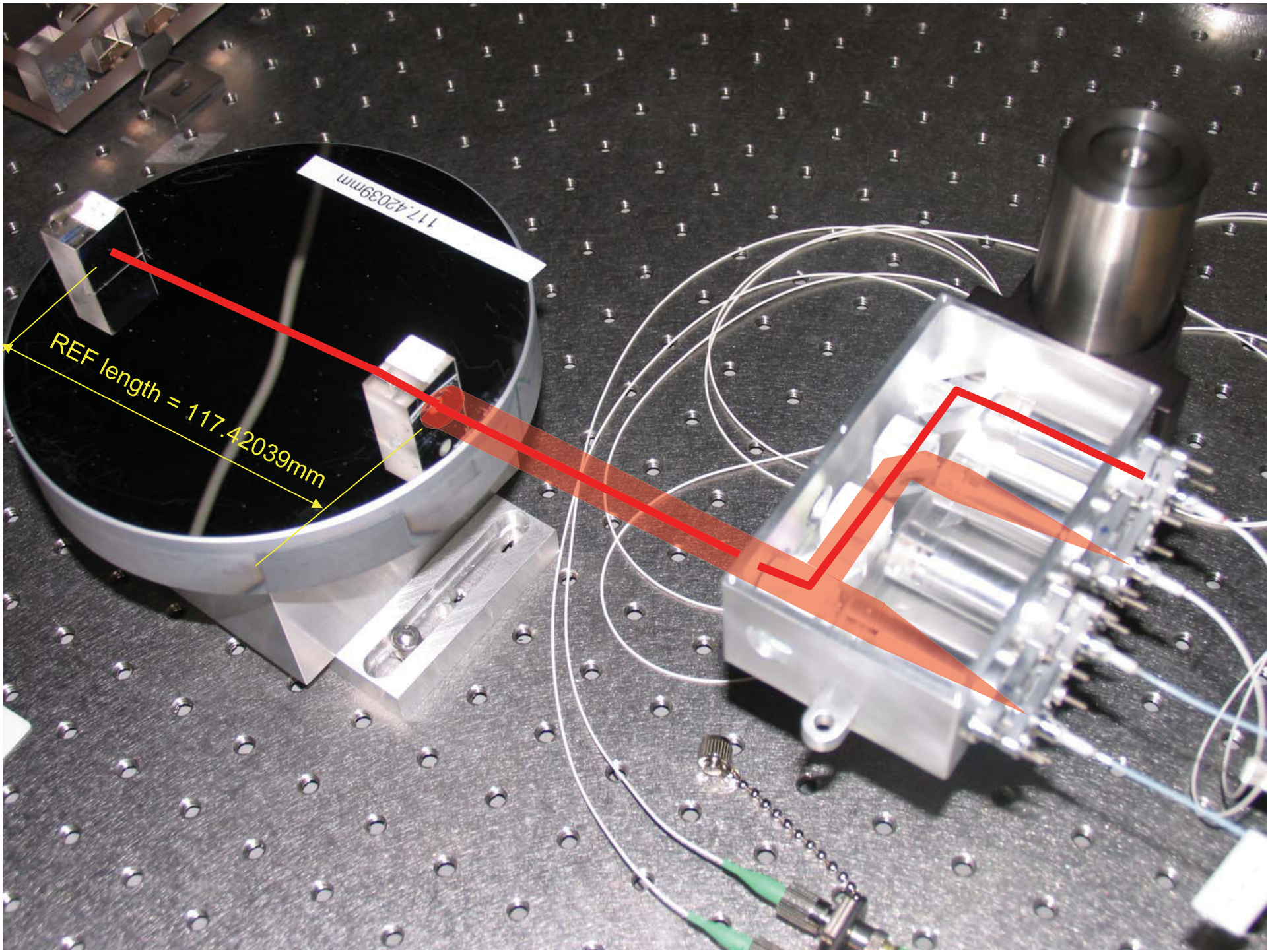
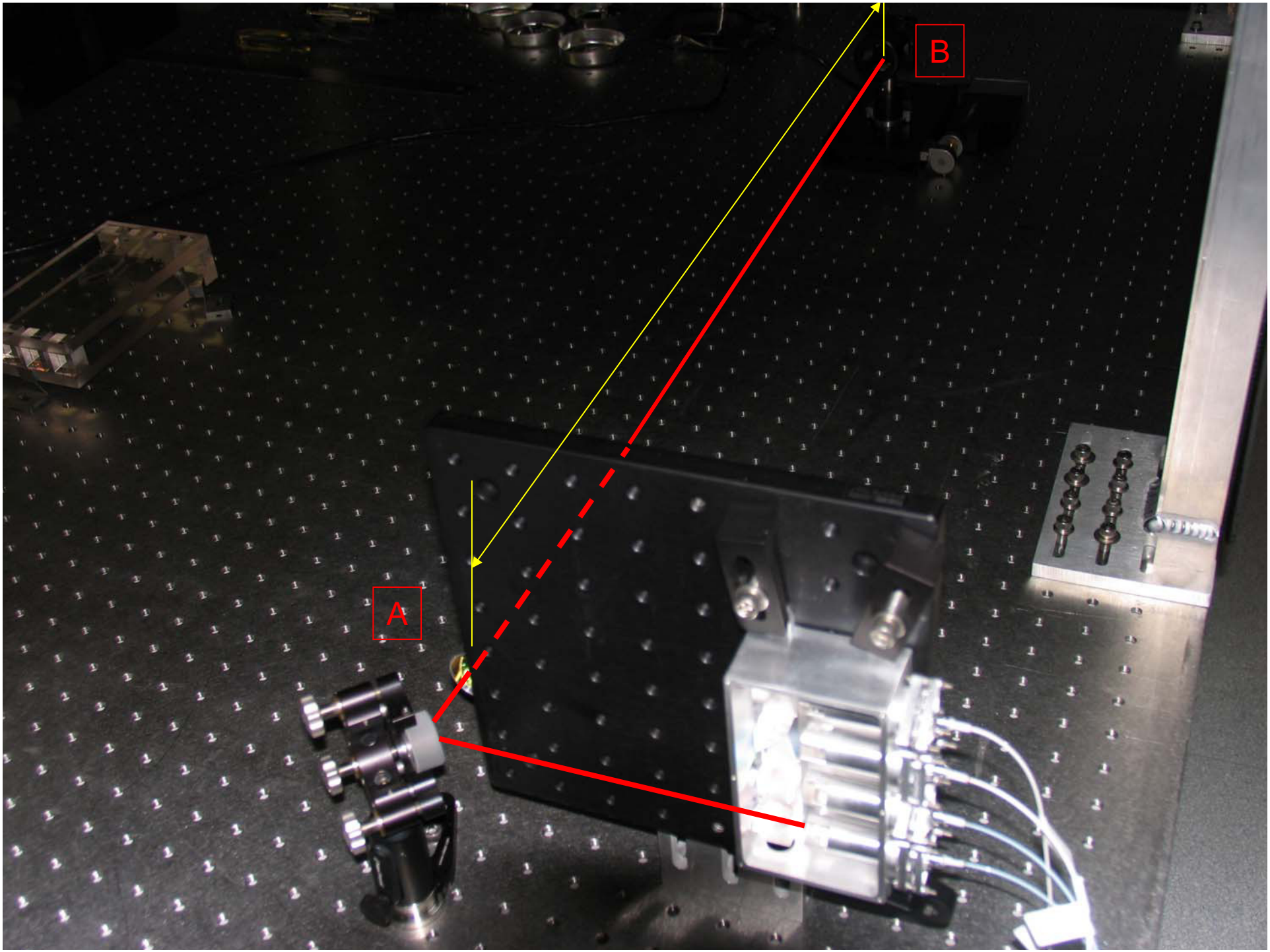

117.42039mm
REF length = 117.42039mm


B
A

Scaling Laws

- 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 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?

Build a very rigid back structure and a simple metrology system or a low-cost back structure and a very capable metrology system to correct for deformations? Where is the optimum?

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