Telescope Development for a Space-based Gravitational Wave Observatory

eLISA Consortium Meeting
12-14 Oct 1 2015

Prepared by Jeff Livas
Shannon Sankar, Peter Blake, John Crow, Joe Howard, Len Seals, Ron Shiri, Garrett West
NASA Goddard Space Flight Center

Guido Mueller, Alix Preston, Pep Sanjuan
University of Florida

Project Objective and Approach

- **Objective:**

> To design, fabricate and test a telescope to verify that it meets the requirements for precision interferometric metrology for space-based gravitational-wave observatories.

- **Key challenging requirements**
  - Optical pathlength stability
  - Scattered light performance
  - Manufacturable design
- **Approach**
  - Develop a telescope design that
    - Meets eLISA technical requirements
    - Can be manufactured (need multiple (~ 10) copies)
    - TRL-5 by CY2018 (nominally for EM model)
  - Commission a study with a commercial optics/telescope vendor for advice on manufacturability
  - Demonstrate we can implement the design

Telescope Requirements

	Parameter	Derived From	eLISA/NGO
1	Wavelength		1064 nm
2	Net Wave front quality departure from a collimated beam of as built telescope subs system over Science field of regard under flight-like conditions	Pointing	$\leqq \lambda/30$ RMS
3	Field-of-Regard (Acquisition)	Acquisition	+/- 200 µrad (large aperture)
4	Field-of-Regard (Science)	Orbits	+/- 20 µrad (large aperture)
5	Field-of-View (Science)	Stray light	+/- 8 µrad (large aperture)
6	Science boresight	FOV, pointing	+/- 1 µrad (large aperture)
7	Telescope subsystem optical path length[1] stability under flight-like conditions	Path length Noise/ Pointing	$\leq 1\, pm/\sqrt{Hz} \times \sqrt{\left(1+\left(\frac{0.003}{f}\right)^4\right)}$ where 0.0001 < f < 1 Hz; 1 pm = 10^{-12} m
8	Afocal magnification	short arm interferometer	200/5 = 40x (+/-0.4)
9	Mechanical length		< 350 mm TBR
10	Optical efficiency (throughput)	Shot noise	>0.85
11	Scattered Light	Displacement noise	< 10^{-10} of transmitted power into +/- 8 µrad Science FOV
	Interfaces: Received beam (large aperture, or sky-facing)		
12	Stop Diameter (D) (large aperture)	Noise/ pointing	200 mm (+/- 2 mm)
13	Stop location (large aperture)	Pointing	Entrance of beam tube or primary mirror
	Interfaces: Telescope exit pupil (small aperture, or optical bench-facing)		
14	Exit pupil location	Pointing	13.5 +/- 2 cm (on axis) behind primary mirror
15	Exit pupil diameter	optical bench	5 mm (+/- 0.05 mm)
16	Exit pupil distortion	SNR	< 10%
17	Exit pupil chief ray angle error		+/- 10 µrad

challenging (row 7)

challenging (row 11)

SGO-Mid = 250 mm

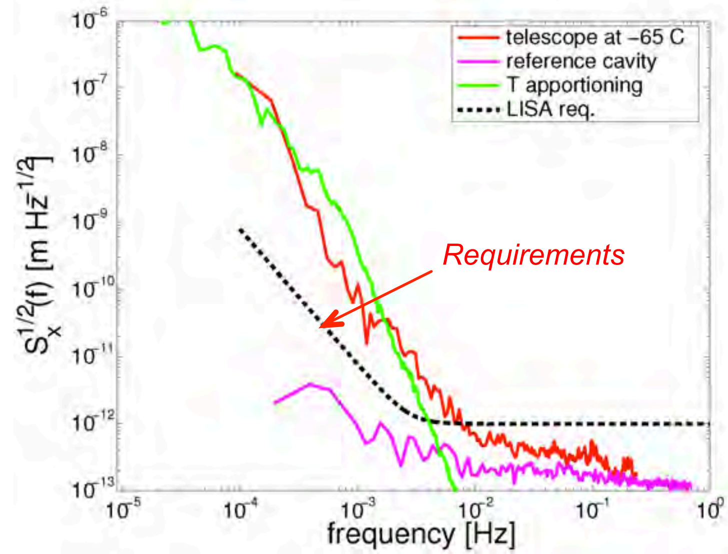
From U of Glasgow bench design, courtesy of Ewan Fitzsimons and Harry Ward

Previous Work: On-axis Telescope Spacer Design

Spacer Activity Objective

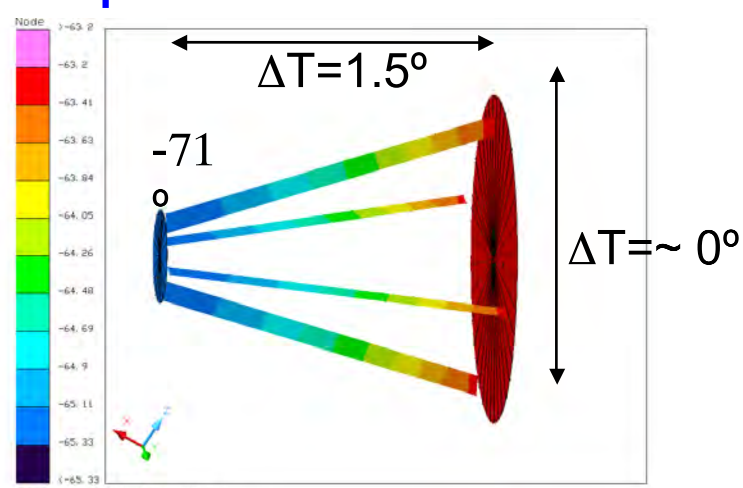
- Develop and test a design for the main spacer element between the primary and secondary mirrors
- M1 - M2 spacing identified as critical by tolerance analysis
- SiC limited by lab thermal fluctuations
- Would meet requirements on orbit

SiC Spacer Design
Can Meet Requirements at -65C



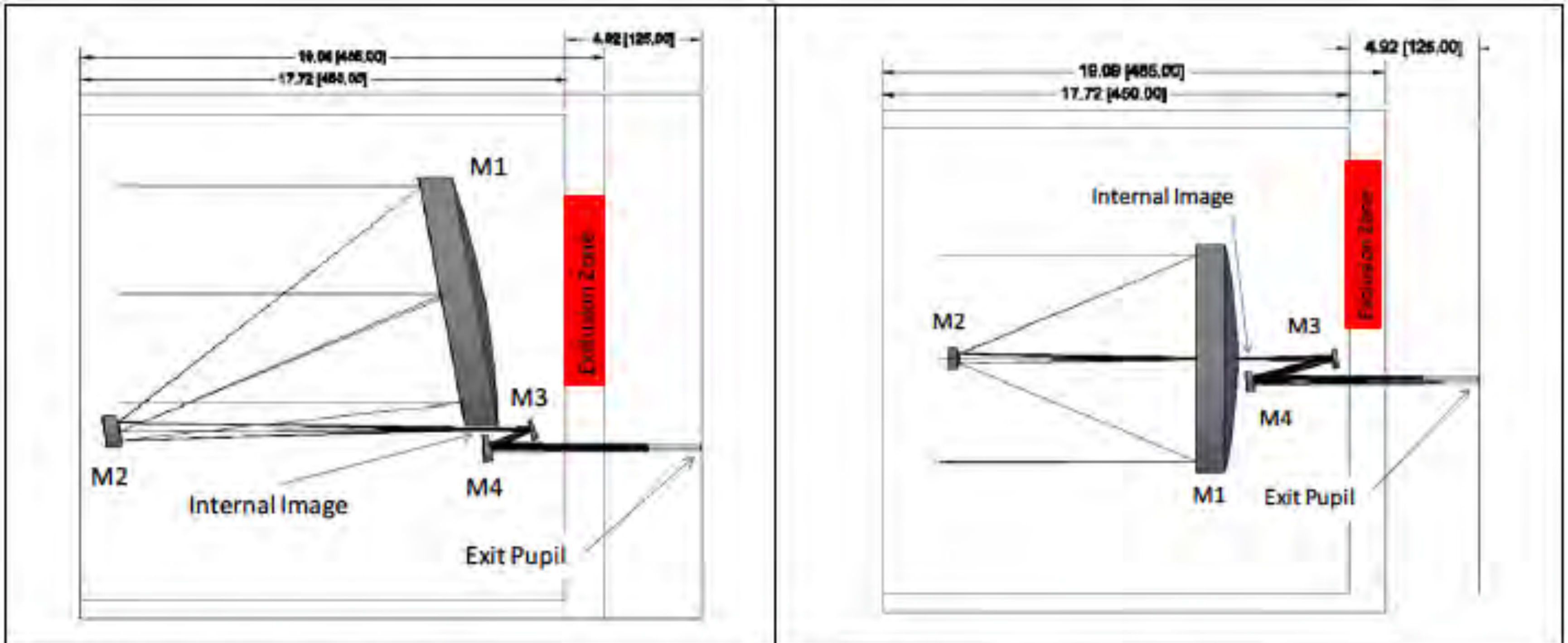
SiC Spacer Design: QuadPod

SiC Spacer Thermal Environment



J. Sanjuan, et al.; Rev Sci Instrum. **83**(11), 116107 (2012).

Commercial Vendor: Designs considered



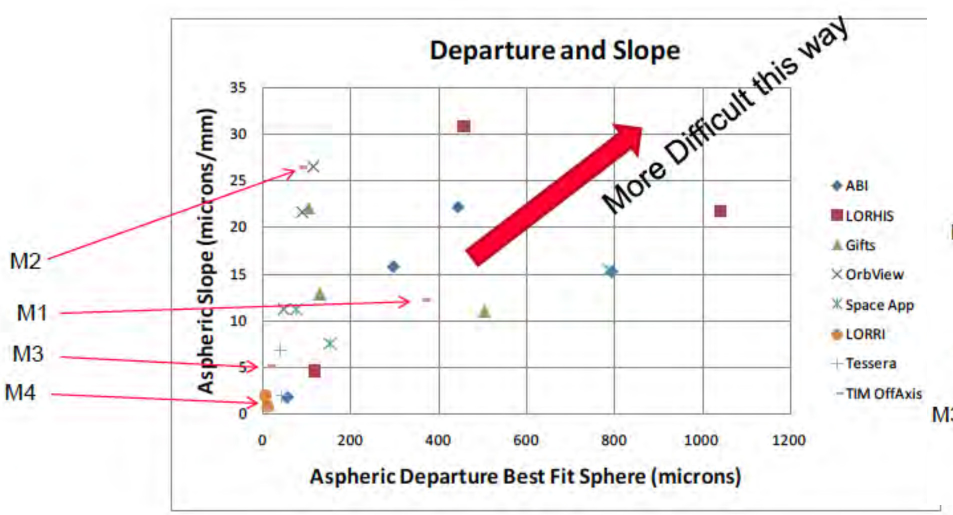
SGO Study Off-axis Design Candidate | SGO On-axis Design Candidate

- **Both designs have the same nominal requirements**
- **Exclusion zone (in red) is for bench optics**

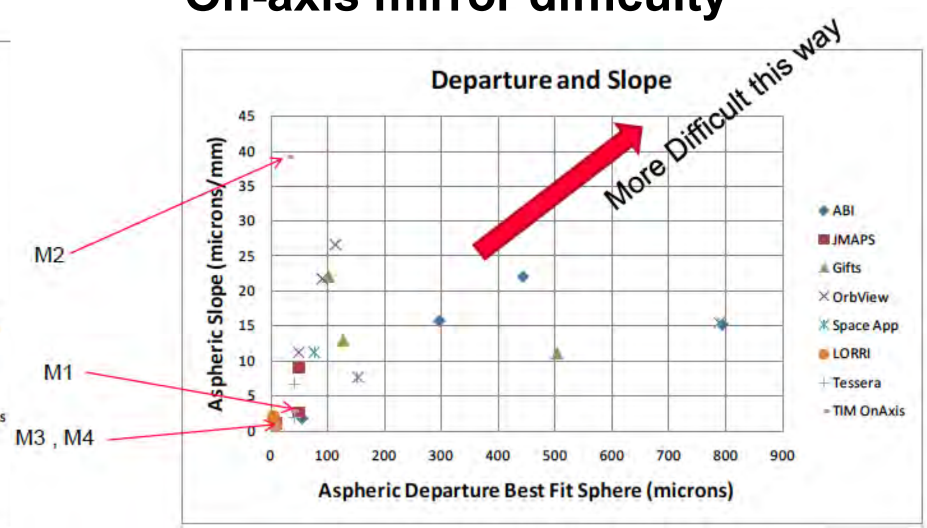
Commercial Vendor: Manufacturability

- **On- vs off-axis mirrors similar in complexity**
- **On- vs off-axis system alignment similar in complexity**
  - Compensation techniques are similar
- **Schedule is 16 months for first copy**
  - Driver is material availability for SiC (study contractor makes material!)
  - Once material is cast, then machining is the bottleneck
  - “pipeline” approach is possible and reduces recurring schedule to ~ 10-12 months/copy

Off-axis mirror difficulty



On-axis mirror difficulty



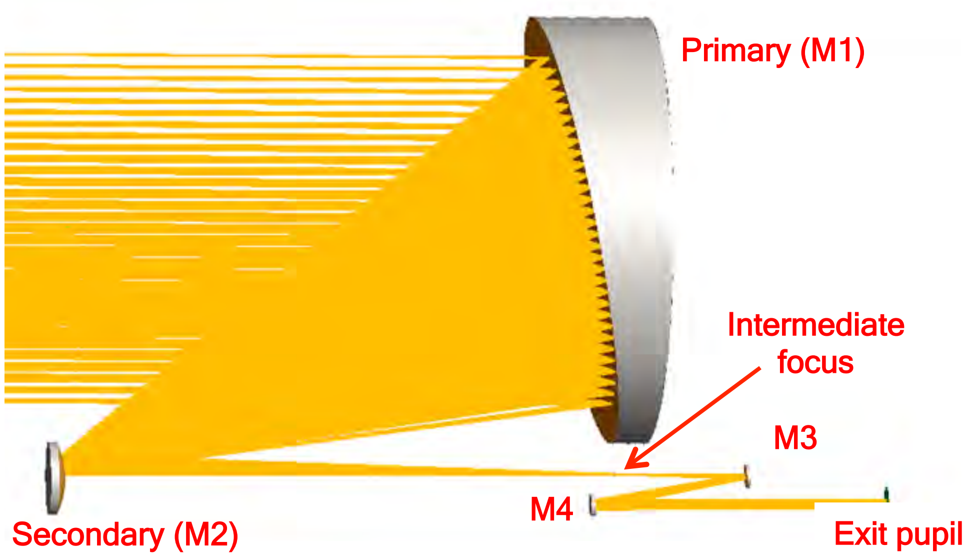
Overall Stability Budget (@ .1 mHz)

- At .1mHz, (worst-case scenario within frequency range), the overall path length stability is divided among the following constituents

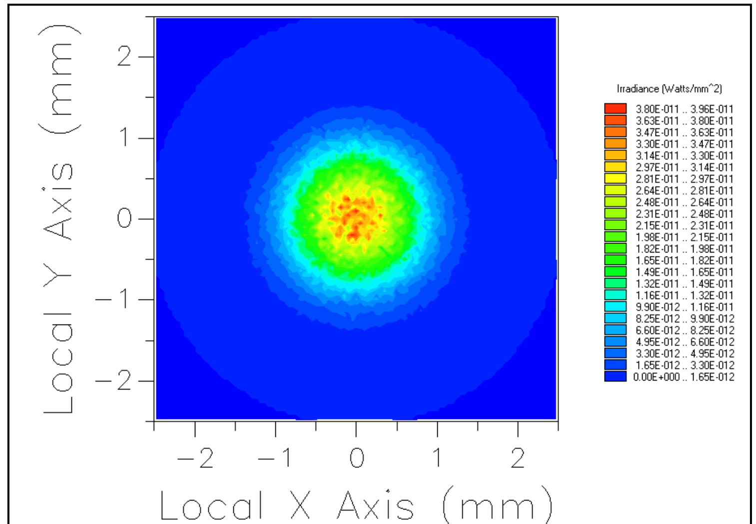
Contributor	P-V OPL Change (picometers)
Thermal	7.075
Creep	5.096
Focus Drive	0.015
Total	**12.19**

- Approach that can meet the requirement has been identified
  - Prediction is just within derived specification (12.28 pm).
  - Further optimization and more detailed error budget appropriate for subsequent phase
- Thermal prediction approach assumes electronics box loading and solar loading are in phase (conservative approach)
  - Can further increase stability through using a third baffle (extra mass)
- Belief is that creep is a conservative estimate; could be reduced with geometric design developments and better understanding of the time dependant stability of the Invar material

Scattered Light Analysis



Pupil Plane Scatter Irradiance



- Source power = 1W
- Total power on the detector = 6.6×10^{-11} W → (barely) meets specification of less than 10^{-10}

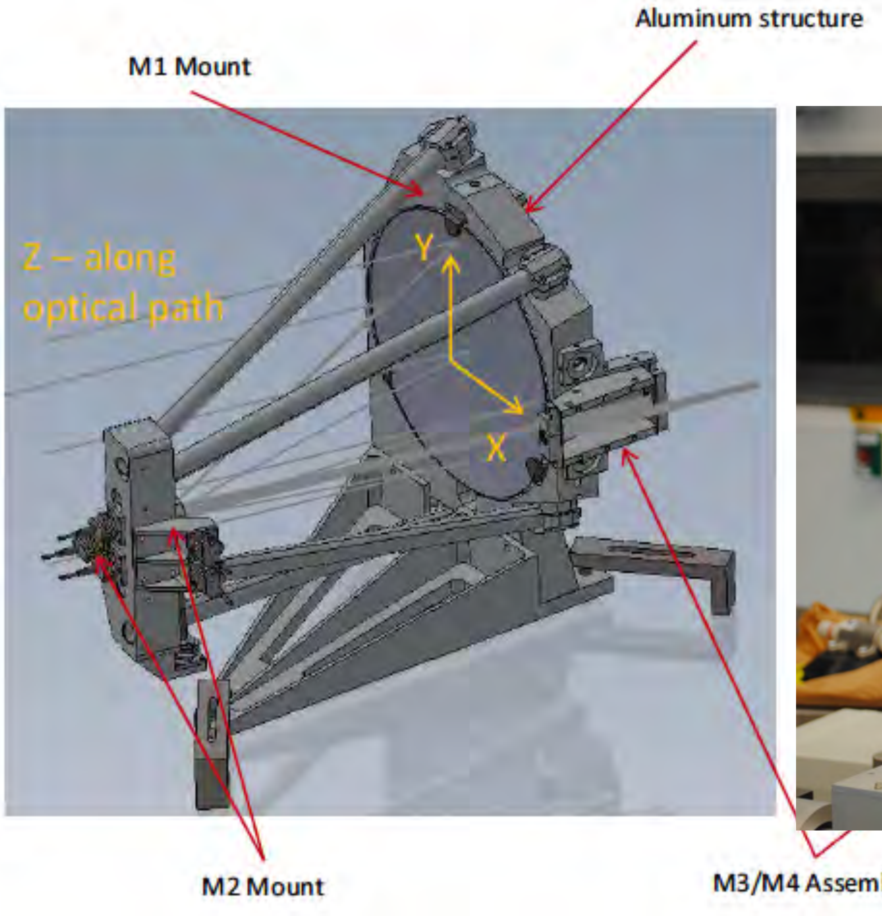
Mirror	RMS surface roughness (Å)	MIL-STD 1246D CL
M1	15	300
M2	15	200
M3	5	200
M4	5	200

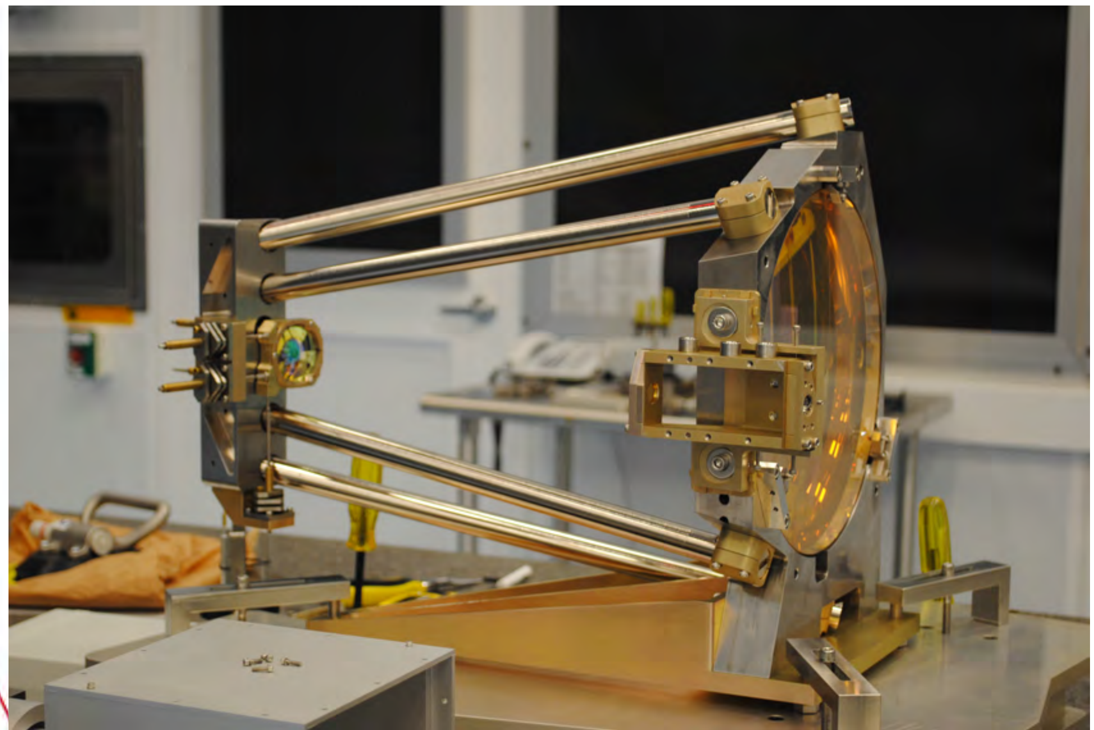
Conflicting accounts of on-orbit levels

mirror	Path#	# Rays	Power %	Power	1st scatter surface
3	7	2291695	74.947	4.9421e-11	.20140417_elisa_baseline.M3.Front
4	3	2711030	23.053	1.5201e-11	.20140417_elisa_baseline.M4.Front
2	11	2565386	1.9733	1.3012e-12	.20140417_elisa_baseline.M2.Front
1	14	1399213	0.026184	1.7266e-14	.20140417_elisa_baseline.M1.Front
Totals		8967324	100	6.5941e-11	

M3 and M4 contribute most of the scattered light on the detector

Prototype Telescope Design

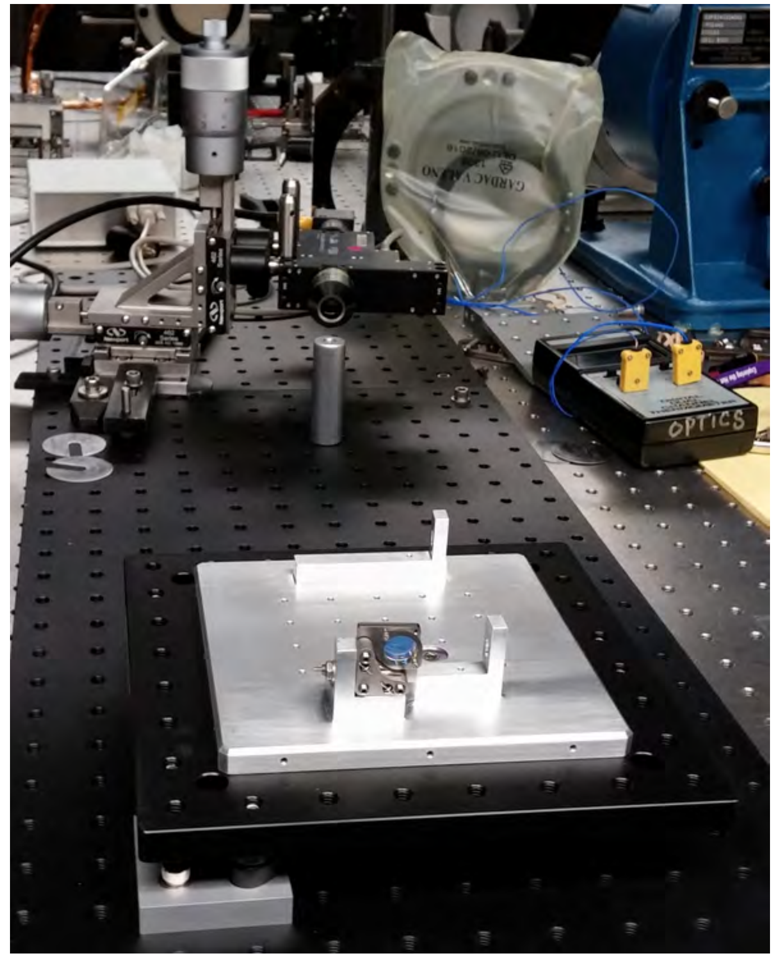




Scattered Light Test Bed

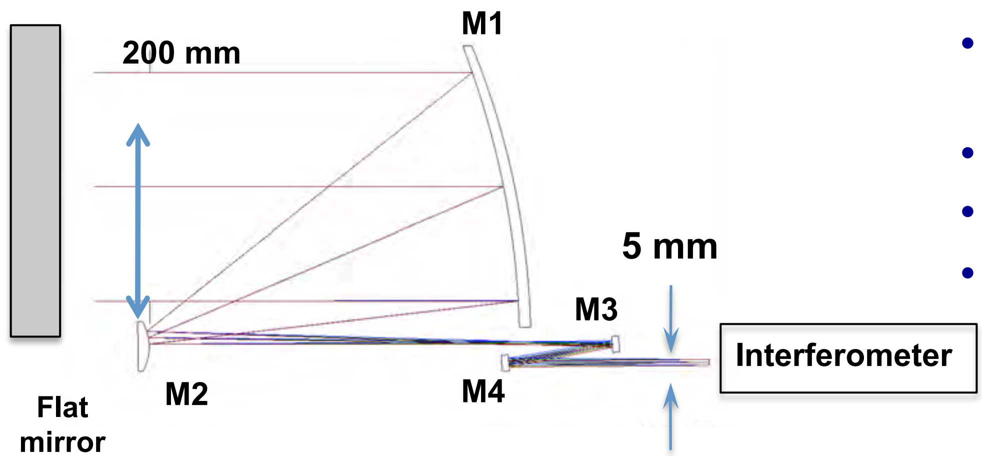
- **Validate scattered light model**
  - Determine surface roughness
    - needed to meet requirements
    - Where particulates become important
  - Components get dirty while making measurements
- **M3/M4 dominate budget**
  - Test M3/M4 separately
    - Faster cycle-time than full telescope
  - Use mirrors with different properties
    - Surface roughness
    - Reflective coatings
    - Surface contamination levels
  - Mirrors need not have telescope prescription for some tests
  - Practice alignment techniques
- **Develop analysis pipeline**
  - BRDF (component level) to predict system level

M3/M4 Scattered Light Test Bed

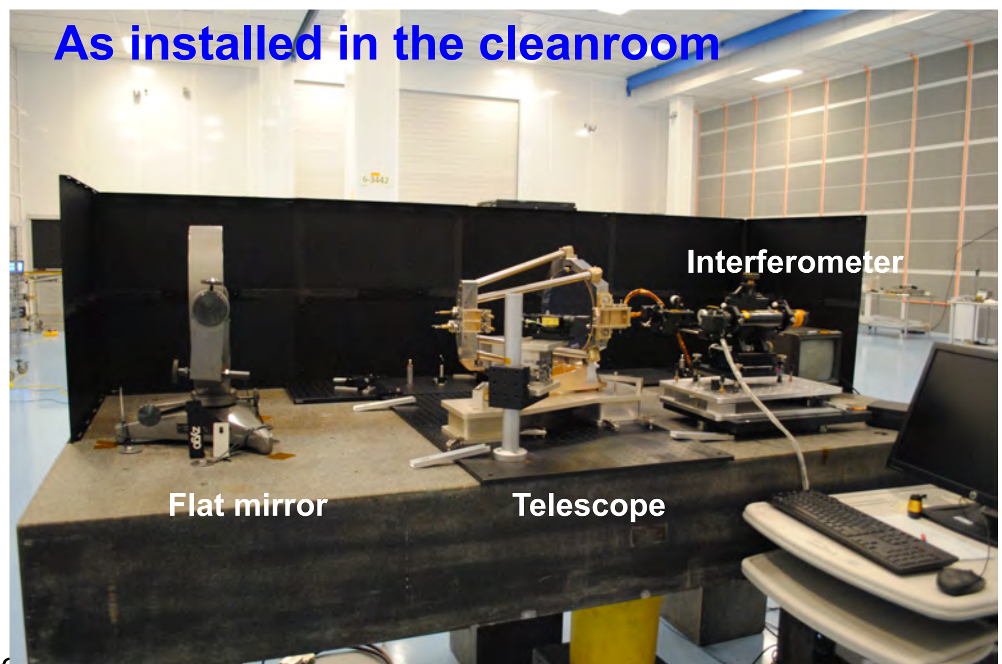


Optical Test Setup

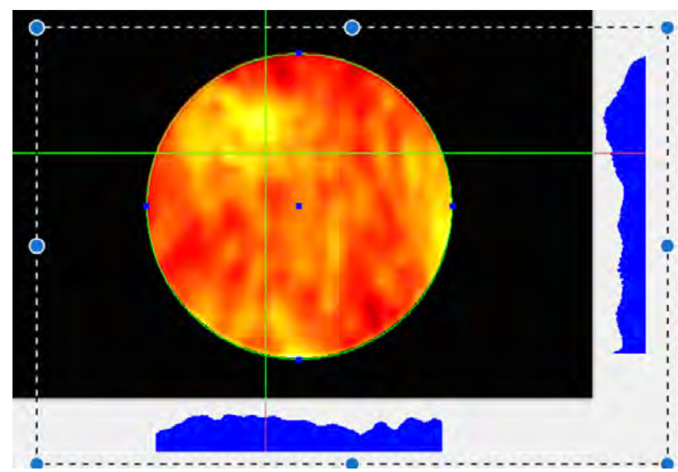
Optical Layout



- Telescope tested double-pass from the small aperture side
- Currently aligned to better than λ/34
- stable under normal lab conditions
- Room temperature operation only



Measured WFE performance
λ/34, center field, 632.8 nm



SUMMARY/NEXT STEPS

- Prototype installed and aligned
    - Delivered to GSFC 6/5/15 (originally 3/20/15)
    - Reassembled and realigned by 7/27/15
- Tested double-pass with an interferometer (LUPI)
- Residual wavefront error is λ/34 (λ/30 spec) at 632.8 nm
- Alignment is stable under laboratory conditions
- Next steps:
    - verify wavefront error at 1064 nm
    - beam dump for transmitted light needed
        - use carbon nanotubes (R < 0.5%)
    - verify scattered light model
- Concern: mirrors are dirty
    - Vendor packaged poorly for shipping
    - May have to try cleaning M1, M2 (no spares)
    - Have clean spares for M3, M4

Particulates on Primary