Telescope Development for a Space-based Gravitational Wave Observatory

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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, $1\text{ pm} = 10^{-12}$ 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

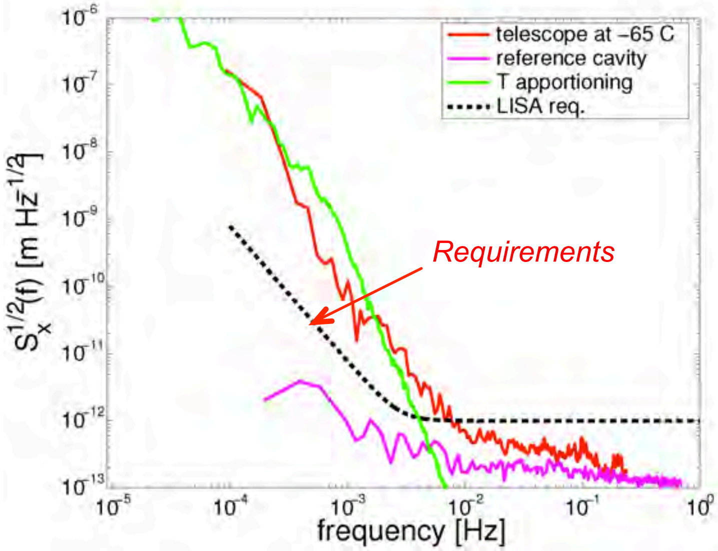
From U of Glasgow bench design, courtesy of Ewan Fitzsimons and Harry Ward

Previous Work: On-axis Telescope Spacer Design

Spacer Activity Objective

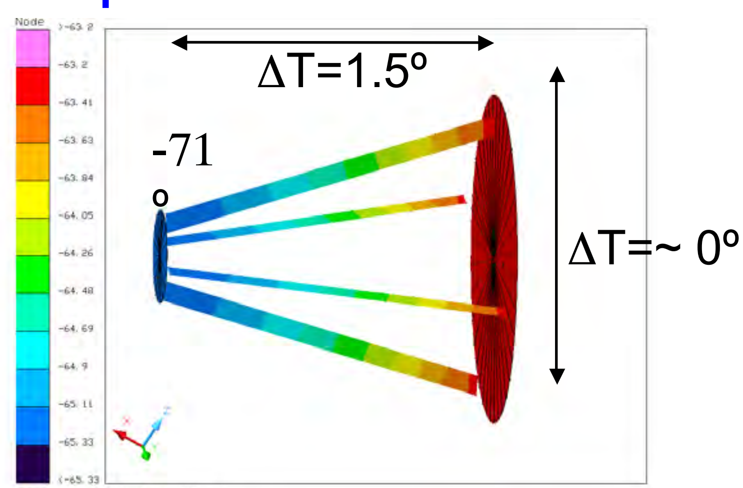
- Develop and test a design for the main spacer element between the primary and secondary mirrors
- M1 - M2 spacing identified as critical by tolerance analysis
- SiC limited by lab thermal fluctuations
- Would meet requirements on orbit

SiC Spacer Design
Can Meet Requirements at -65C



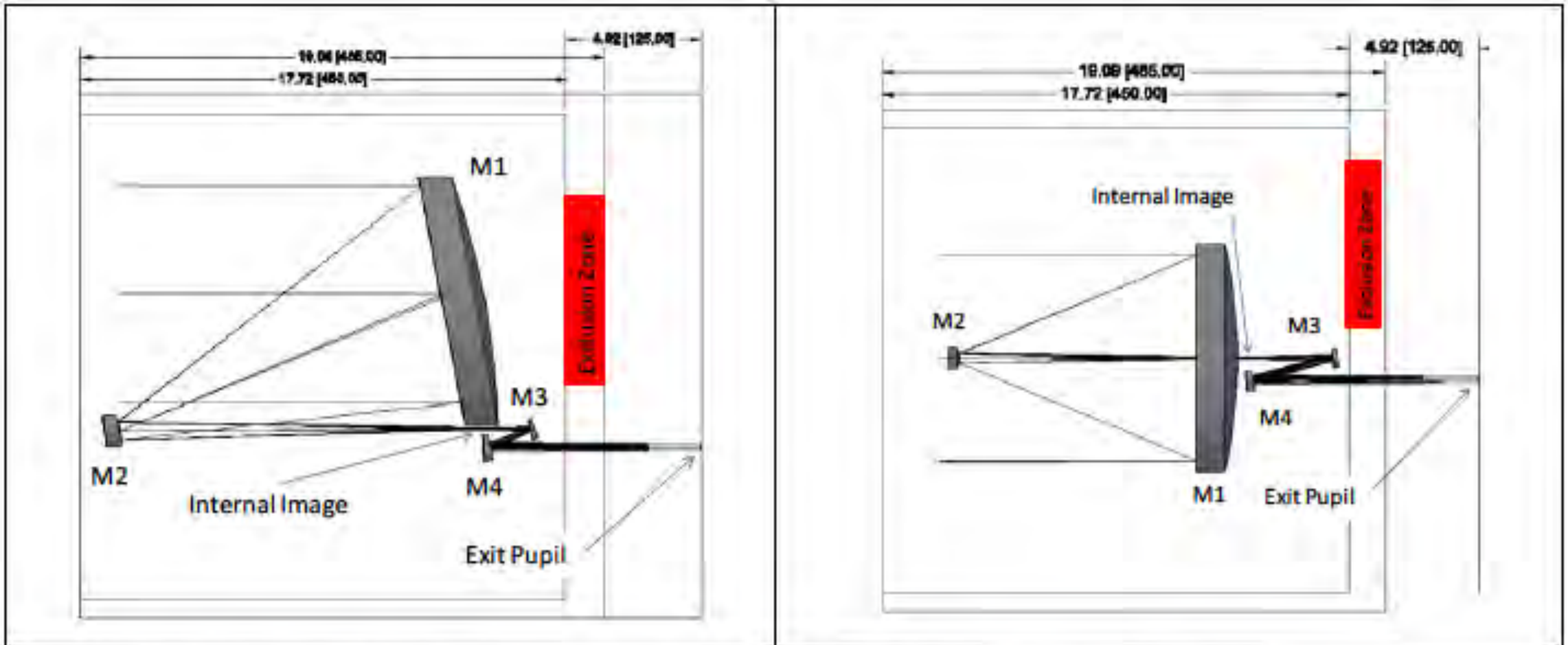
SiC Spacer Design: QuadPod

SiC Spacer Thermal Environment



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

Commercial Vendor: Designs considered



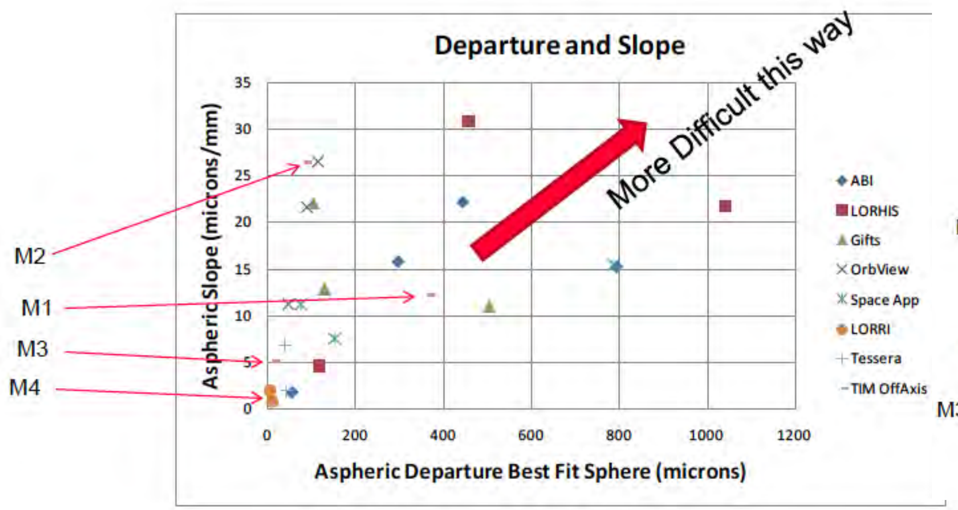
SGO Study Off-axis Design Candidate	SGO On-axis Design Candidate

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

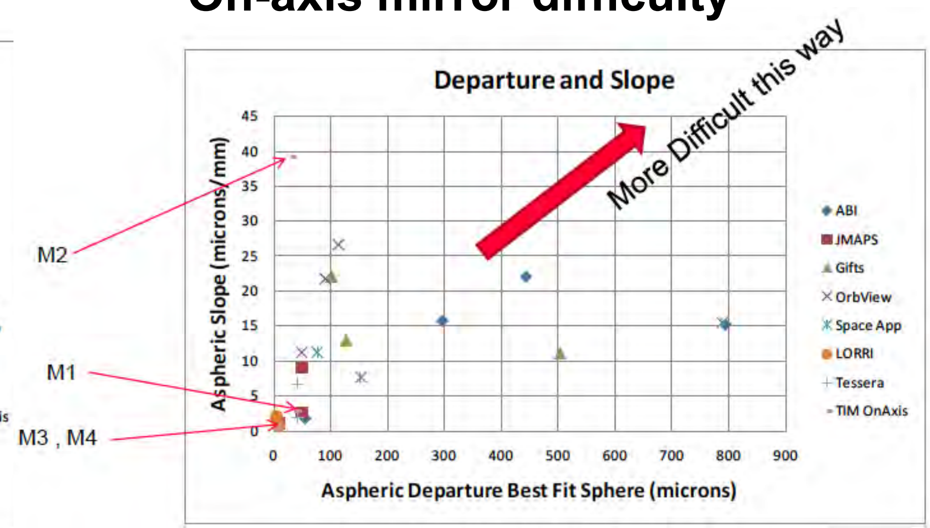
Commercial Vendor: Manufacturability

- **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



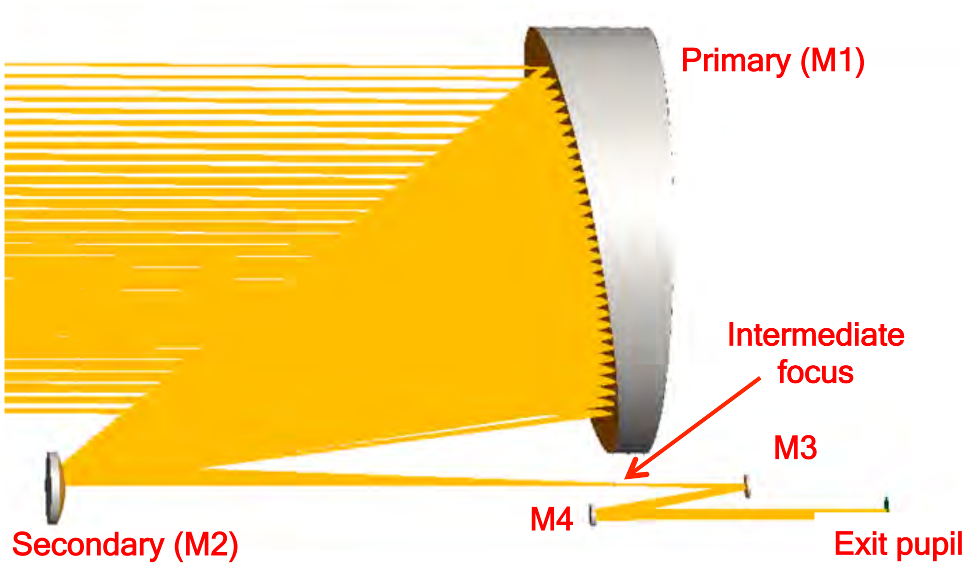
Overall Stability Budget (@ .1 mHz)

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

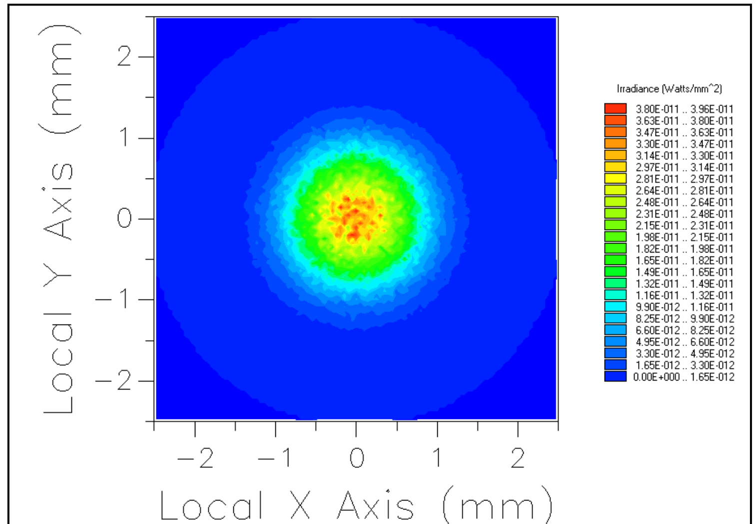
Contributor	P-V OPL Change (picometers)
Thermal	7.075
Creep	5.096
Focus Drive	0.015
Total	**12.19**

- 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}

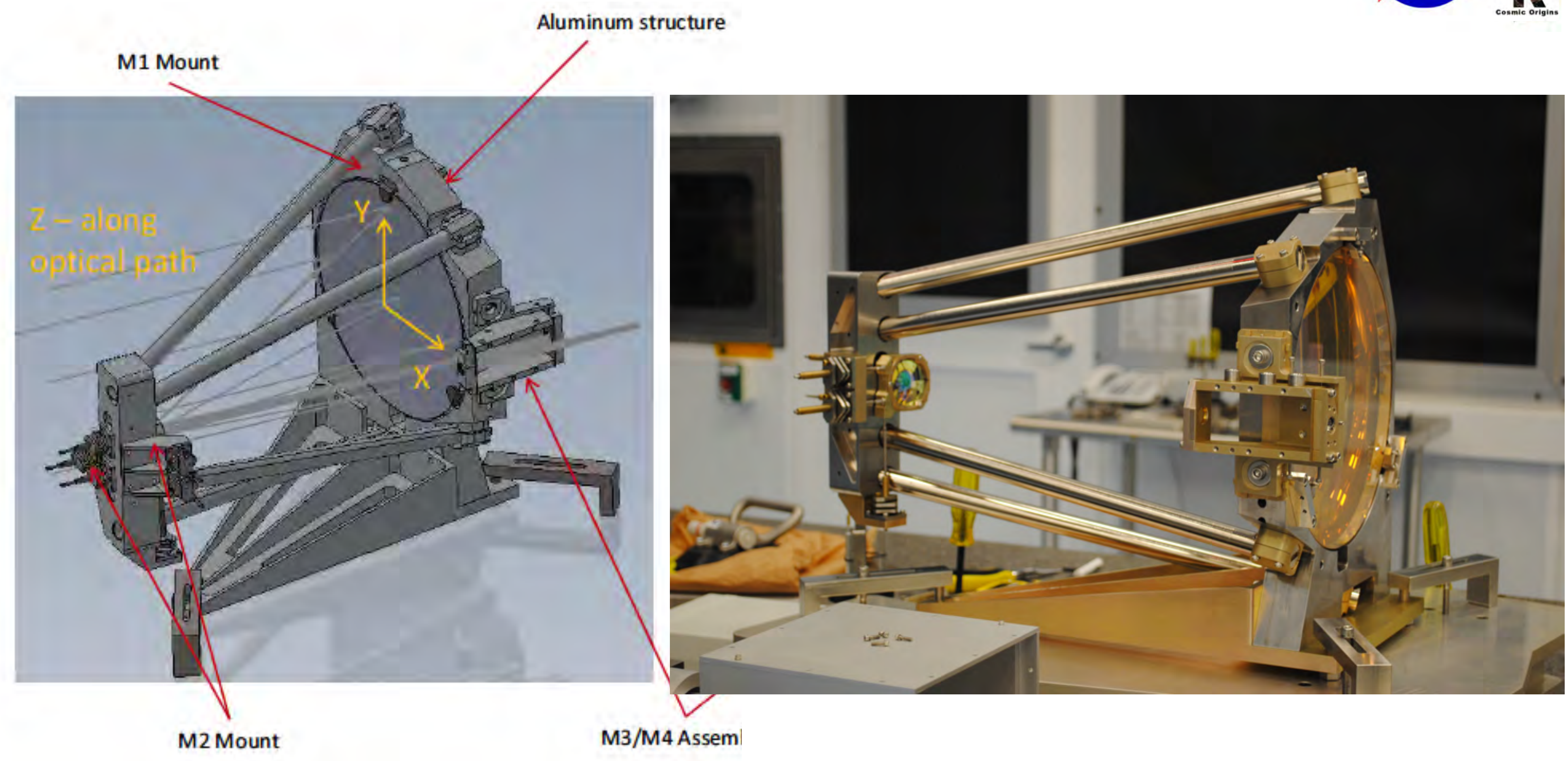
Mirror	RMS surface roughness (Å)	MIL-STD 1246D CL
M1	15	300
M2	15	200
M3	5	200
M4	5	200

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

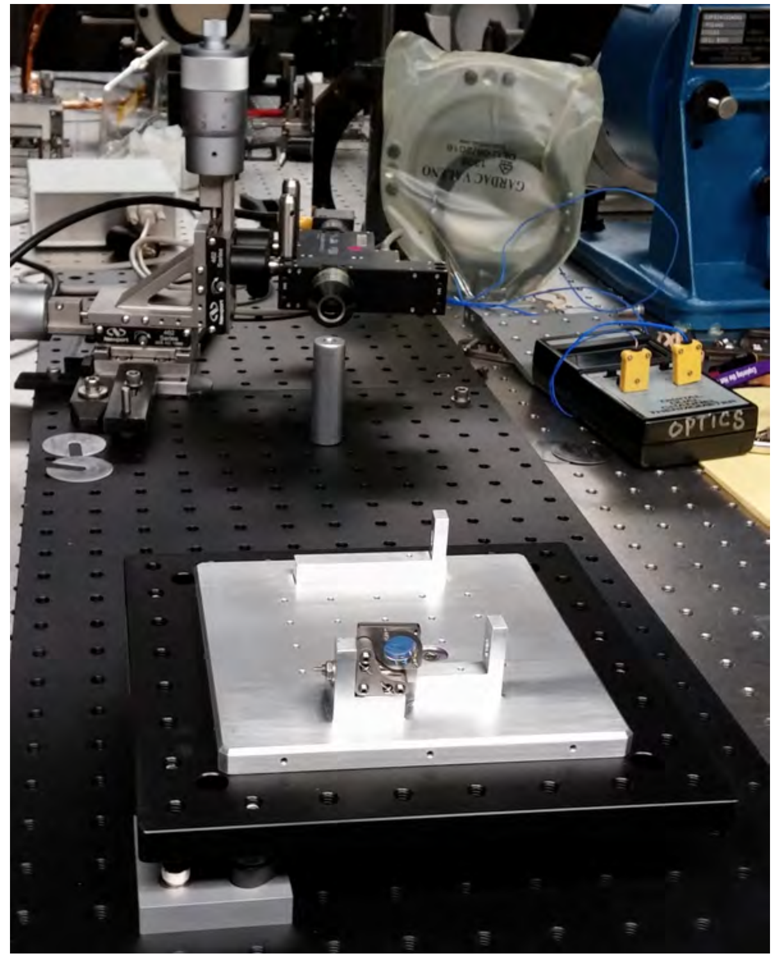
Prototype Telescope Design



Scattered Light Test Bed

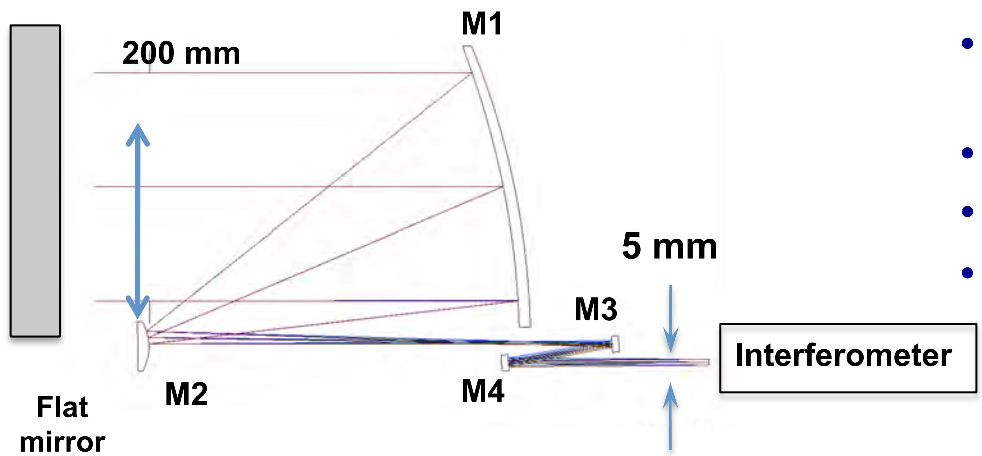
- **Validate scattered light model**
  - Determine surface roughness
    - needed to meet requirements
    - Where particulates become important
  - Components get dirty while making measurements
- **M3/M4 dominate budget**
  - Test M3/M4 separately
    - Faster cycle-time than full telescope
  - Use 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

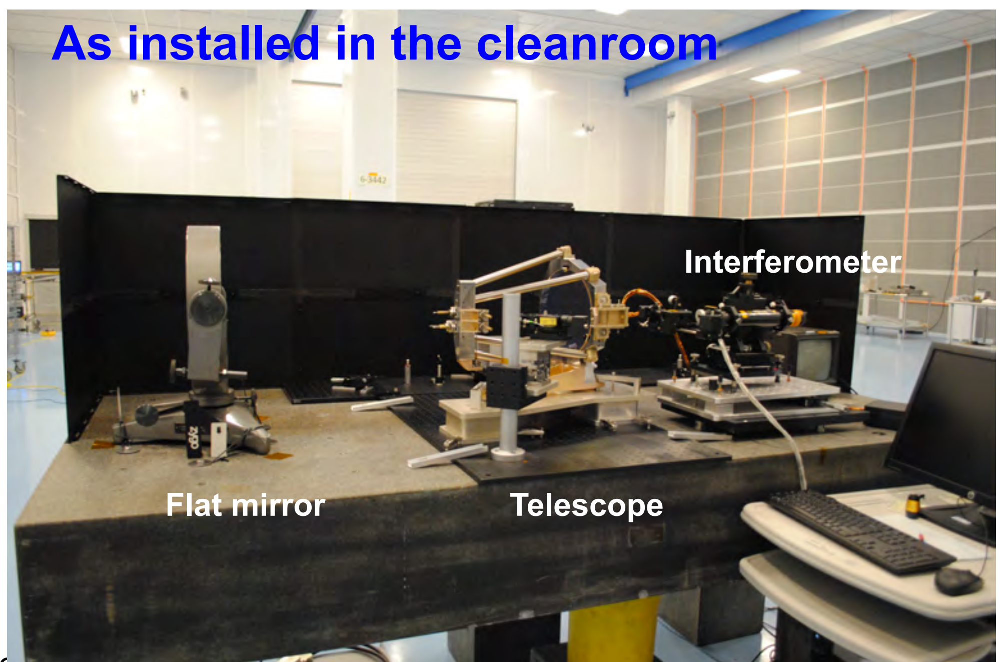


Optical Test Setup

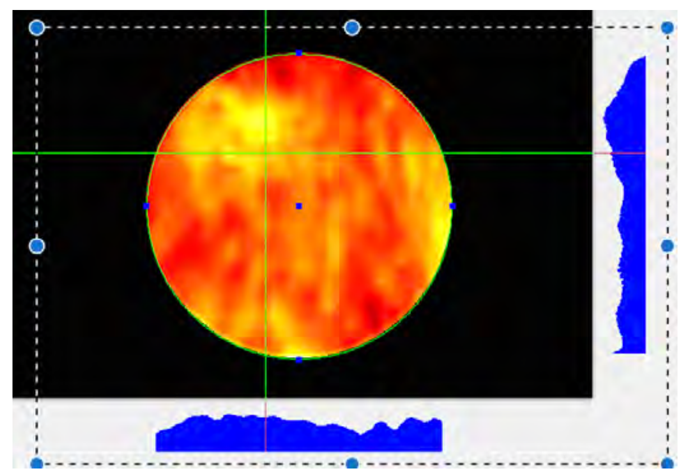
Optical Layout



- 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