Optical Telescope Design Study Results

10th International LISA Symposium

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See also poster #19: Shannon Sankar
UF and GSFC
Telescope Design for a Space-based Gravitational-wave Mission

Outline

- **Research program context**
  - Study to answer key questions
  - Build a prototype based on the study
- **Study Objectives and Approach**
- **Results**
- **Specific Trades**
  - Stability
  - Stray light
  - Materials choice
  - Design form (on- vs off-axis)
  - Manufacturability
- **Lessons learned**

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.

- **Approach**
  - Develop a telescope design for a space-based gravitational wave mission (eLISA as initial target)
    - Meets technical requirements
    - Can be manufactured (need multiple (~ 10) copies)
    - TRL-5 by CY2018 (nominally – may have been overcome by events)
  - Demonstrate we can implement the design
- **Key challenging requirements**
  - Optical pathlength stability
  - Scattered light performance
  - Manufacturable design

Design Study Goals

- **The purpose of the Study is to get experienced advice**
- **Key Questions**
  - Can an on-axis design meet requirements? OR
  - Can an off-axis design (assumed to meet requirements) be manufactured?

Trade-off Summary

Design	WFE with temperature gradient	Scattered Light	Manufacturability (need 10)
On-Axis	+	-	+
Off-Axis	-	+	-

- **Deliverables (from Section 4.0 of the Statement of Work)**
  - Complete mechanical, optical, and thermal design
  - Test plan for verifying and validating requirements
  - Manufacturing plan (need 10 identical telescopes), including schedule
  - ROM cost estimate with and without testing for 10 telescopes

DESIGN STUDY:
SUMMARY AND RESULTS

Study Summary

- **Industial Study Schedule**
  - 1 Nov 2012 Kicked off
  - 17 Jan 2013 Mid term Technical Interchange Meeting (TIM)
  - 11 April 2013 Final report (23 weeks)
  - Original bid was 4 months (16 weeks)
  - Not-to-exceed was 6 months (24 weeks)
- **Main results**
  - Off-axis design for stray light
    - Claim alignment and test similar for on- and off-axis designs (both complex)
  - Silicon carbide structure to avoid schedule hit from composite outgassing
    - Composite more stable dimensionally due to CTE
    - SiC has lower RE cost
  - ROM ground prototype
    - $2.5M= $1.58M RE + $0.26M NRE + $0.43M testing + $0.22M focus mechanism
    - 16 months delivery

DESIGN STUDY: REQUIREMENTS AND BOUNDARY CONDITIONS

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)

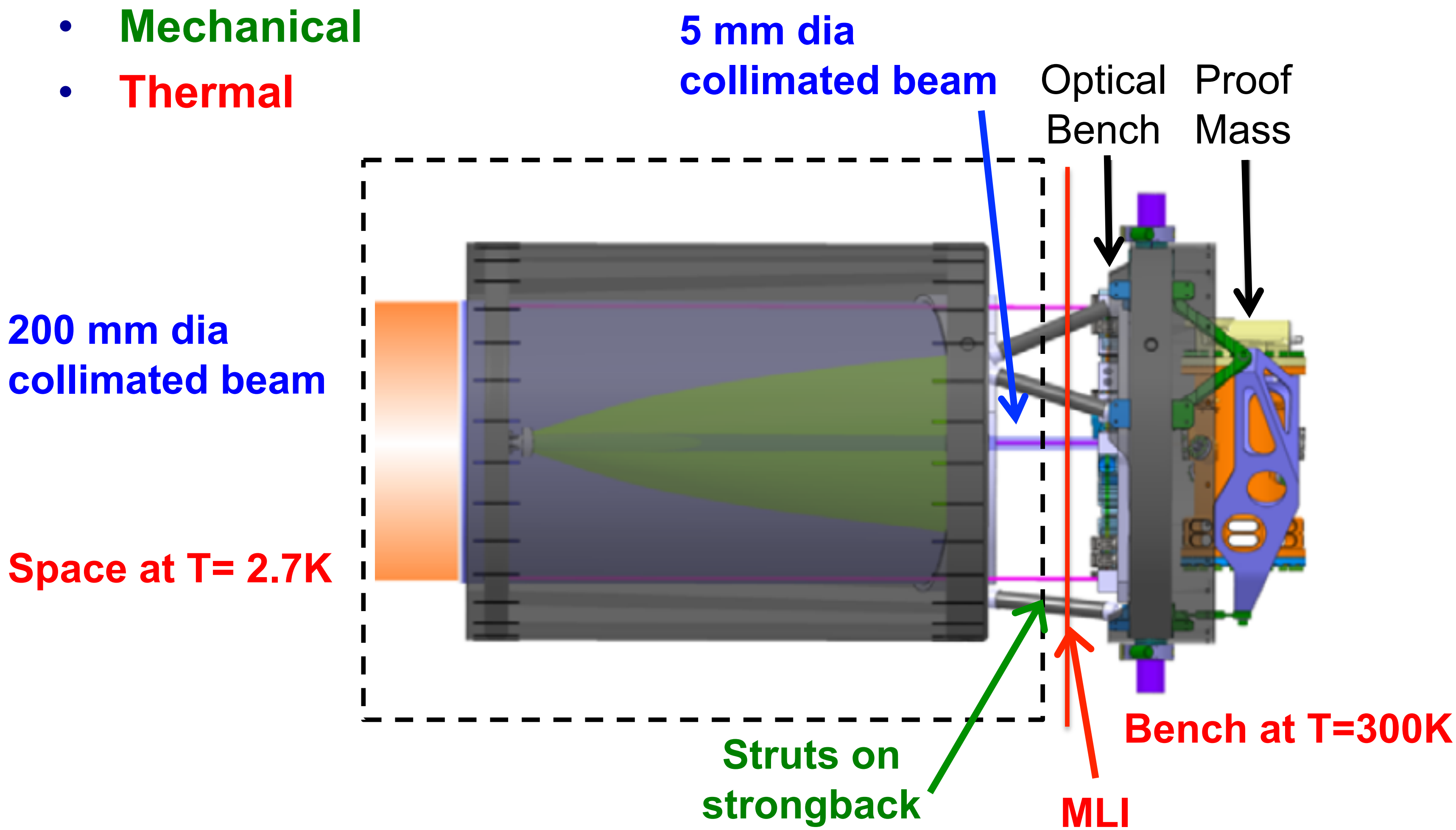
challenging (row 11)

SGO-Mid = 250 mm (row 12)

From U of Glasgow bench design, courtesy of Ewan Fitzsimons and Harry Ward (rows 14–17)

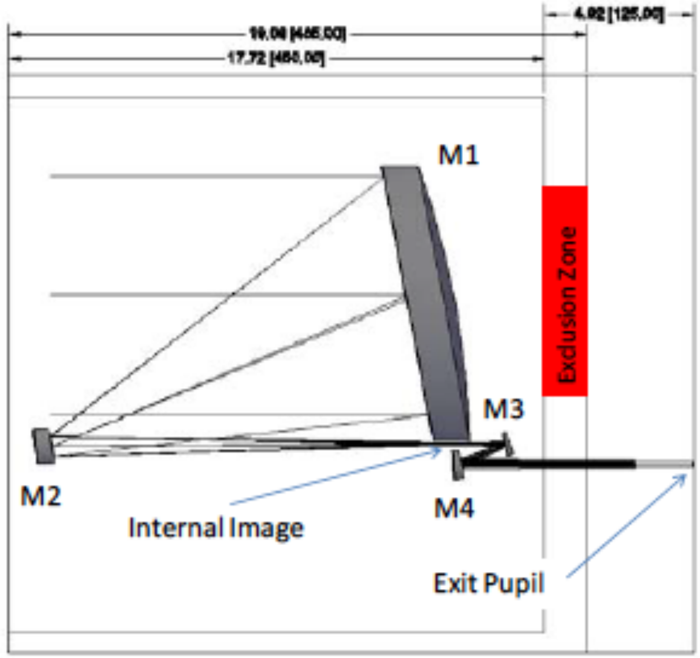
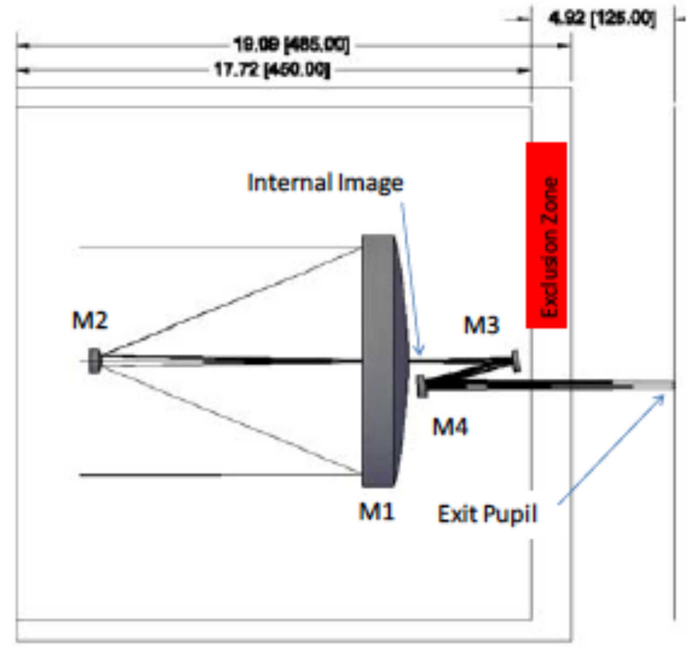
Key Telescope Interfaces

- Optical
- Mechanical
- Thermal



DESIGN STUDY: RESULTS

Designs considered

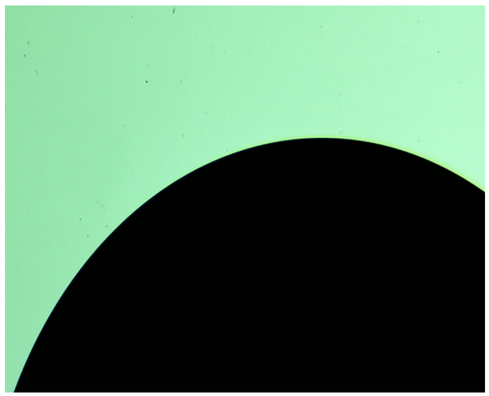
	
SGO Study Off-axis Design Candidate	SGO On-axis Design Candidate

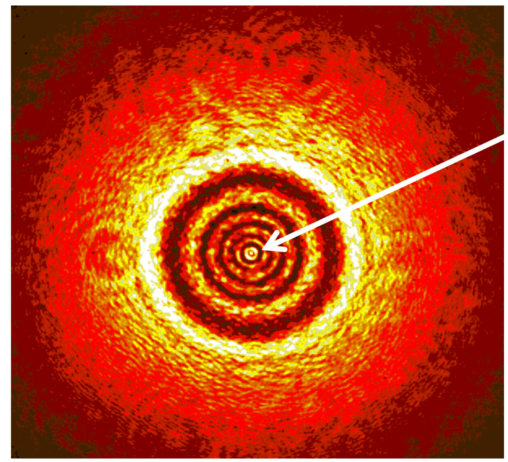
- **Both designs have the same nominal requirements**
- **Exclusion zone (in red) is for bench optics**

Scatter-suppression masks

Why you cannot just drill a hole in the secondary mirror:

Smooth pattern

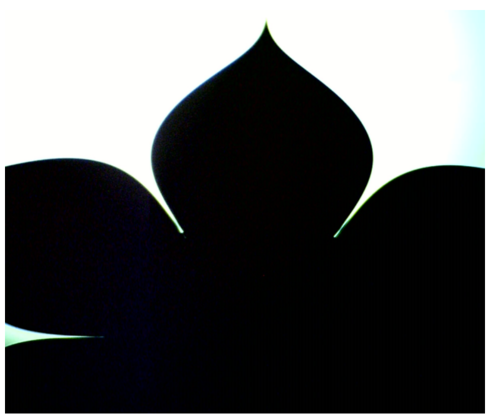


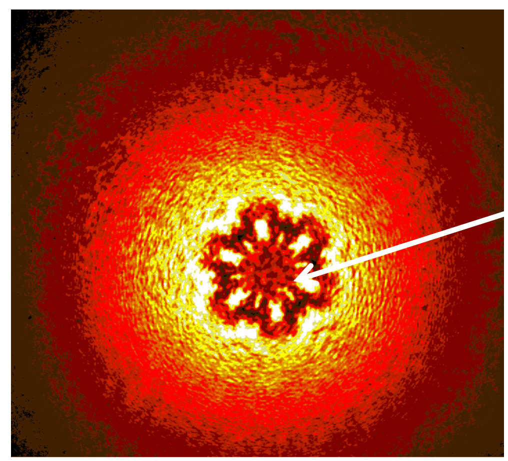


Poisson Spot

Graphics and data courtesy Shannon Sankar and Ryan Stein

Petaled Mask





Poisson Spot Suppressed

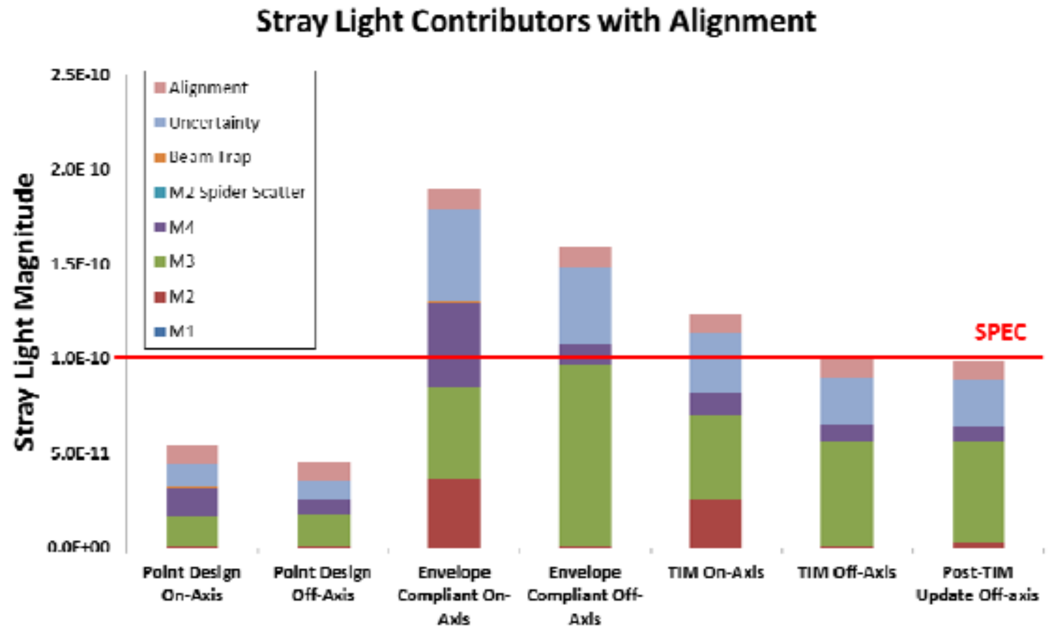
Overall Stability Budget (@ .1 mHz)

- 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

Stray Light Performance



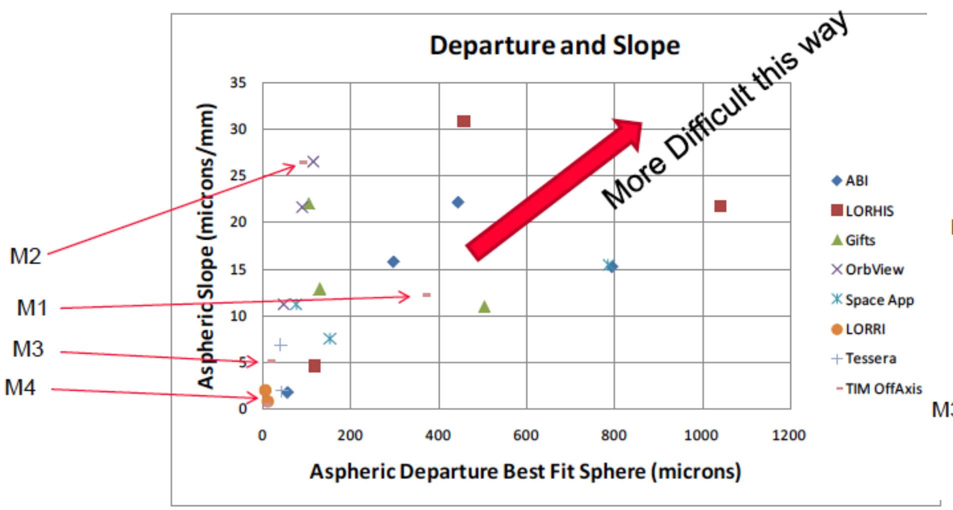
SGO Straylight Results							
	Point Design On-Axis	Point Design Off-Axis	Envelope Compliant On-Axis	Envelope Compliant Off-Axis	TIM On-Axis	TIM Off-Axis	Off-Axis Post-TIM Update
M1	< 1.00E-15	1.30E-14	5.80E-14	1.40E-15	5.40E-14	< 1.00E-15	< 5.0E-14
M2	6.00E-13	4.60E-13	3.60E-11	7.40E-13	2.60E-11	7.00E-13	2.43E-12
M3	1.60E-11	1.70E-11	4.90E-11	9.60E-11	4.40E-11	5.60E-11	5.43E-11
M4	1.50E-11	8.00E-12	4.47E-11	1.10E-11	1.20E-11	8.80E-12	7.32E-12
M2 Spider Scatter	1.40E-13	n/a	1.40E-13	n/a	1.40E-13	n/a	n/a
Beam Trap	2.50E-13	n/a	2.50E-13	n/a	2.50E-13	n/a	n/a
Alignment	1E-11	1E-11	1E-11	1E-11	1E-11	1E-11	1E-11
Uncertainty	1.21E-11	9.6E-12	4.91E-11	4.06E-11	3.11E-11	2.47E-11	2.41E-11
Total	**5.41E-11**	**4.51E-11**	**1.89E-10**	**1.58E-10**	**1.24E-10**	**1.00E-10**	**9.82E-11**

M3 dominates

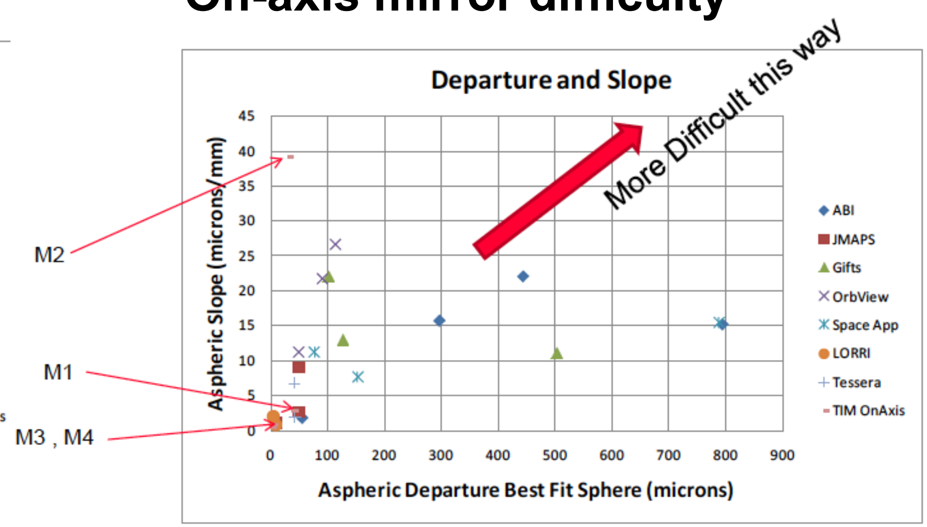
Manufacturability

- **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



Trade Study Overview

Petaled mask research

		Si/SiC		Glass/Graphite Composite	
		On-Axis	Off-Axis	On-Axis	Off-Axis
Manufacturing	Optics	M2 beam trap/spot implementation	standard practice	M2 beam trap/spot implementation	standard practice
Manufacturing	Structure	heritage	heritage	heritage	heritage
Manufacturing	Alignment	standard practice	standard practice	standard practice	standard practice
Environmental Test	Thermal Vacuum	standard practice	standard practice	Standard practice CME / Outgassing considerations	Standard practive CME / Outgassing considerations
Environmental Test	Launch Loads	heritage design and strength	heritage design and strength	heritage design and strength	heritage design and strength
Environmental	Stability	Prior Setup Verification Required; DMI or Mach-	Prior Setup Verification Required; DMI or Mach-Zender Test	Prior Setup Verification DMI or Mach-Zender Test; CME considerations	Prior Setup Verification DMI or Mach-Zender Test; CME considerations
		optics / testing	wer for structure / optics / testing	higher for structure / optics / testing	higher for structure / optics / testing
Schedule		Optic procurement drives schedule	Optic procurement drives schedule	Structure procurement / Testing drives schedule	Structure procurement / Testing drives schedule
Stability	Thermal analysis	Can meet requirements	Can meet requirements	Can meet requirements after outgassing (risk long term)	Can meet requirements after outgassing (risk long term)
Stability	Manufacturing & Material Variability	Use of Invar in metering path	Use of Invar in metering path	Use of Invar in metering path; Long term CME effects	Use of Invar in metering path; Long term CME effects
Stray light		M2 beam trap/spot implementation and native performance	standard practices	M2 beam trap/spot implementation and native performance	standard practices

Did not understand testing requirements

Low risk
Increased risk
High risk

Design Study: Lessons Learned

- **Very difficult to design the telescope by itself**
  - Thermal specifications most difficult
    - Vendor did not know how to handle temperature variation with time
    - interface specs necessary but not sufficient
    - Eventually gave them our spacecraft thermal design
    - Simplified design compliance criteria to check lowest frequency point only
  - Scattered light specifications very challenging
    - Models are not well understood at these low levels
    - Only surface roughness and some contamination modeled
    - No polarization information
    - Field of view as seen by the detector difficult to implement in practice
      - Results not always the same with what should be equivalent approaches
      - Staffing changed mid-way through the study and approach changed
- **Pathlength stability spec not understood**
  - Proposed tests confuse CTE with stability
  - Invar mirror mount estimated creep is nearly half of the overall budget
- **Vendor heritage experience not as helpful as expected**
  - On- vs off-axis experience seemed to act to raise on-axis complexity to match off-axis: demonstrated heroics vs "typical" design
  - What they said: compensation techniques make both designs similar

Testing is essential to validate design/modeling

Summary

- **Industrial Study recommended an off-axis silicon carbide design**
  - May be right answer, but for the wrong reasons
    - Off-axis complexity/performance comparisons not compelling (on-axis comparison may be needlessly complex)
    - Silicon carbide chosen for schedule risk due to moisture absorption in composites (not for performance)
  - Probably one of the best vendors out there, and they did not understand the specs
  - Scattering suppression studies are to “hedge our bets”
- **A realistic TRL-5 prototype is expensive**
  - Materials and processing are expensive
  - Environmental testing is expensive (mid-TRL work is expensive…)
  - Challenging specs are expensive and risky if vendors lack knowledge and experience
- **Forced to re-scope goals**
  - Set understanding models and design process as a higher priority than achieving performance
  - Stray light is the priority for this round; earlier stability testing with a SiC spacer[1]
- **Modeling must be verified by testing**
  - Very small values for scattered light require importance sampling techniques: uncertainty
  - Very small pathlength change values require large dynamic range in calculations
    - Magnified thermal perturbations to be able to see the pathlength changes, then scaled results
    - No obvious problems detected
    - FRED has high dynamic range, CodeV/Zemax do not

[1]J. Sanjuan et al, *Rev Sci Intrum.* **83**(11), 116107 (2012)