eLISA Telescope In-Field Pointing and Scattered Light Study

LISA Symposium Zürich 2016

Jeff Livas[1], Shannon Sankar[1], Garrett West[1], Len Seals[1], Joe Howard[1], with help/advice from Ewan Fitzsimons[2]

[1]NASA Goddard Space Flight Center, Greenbelt, MD

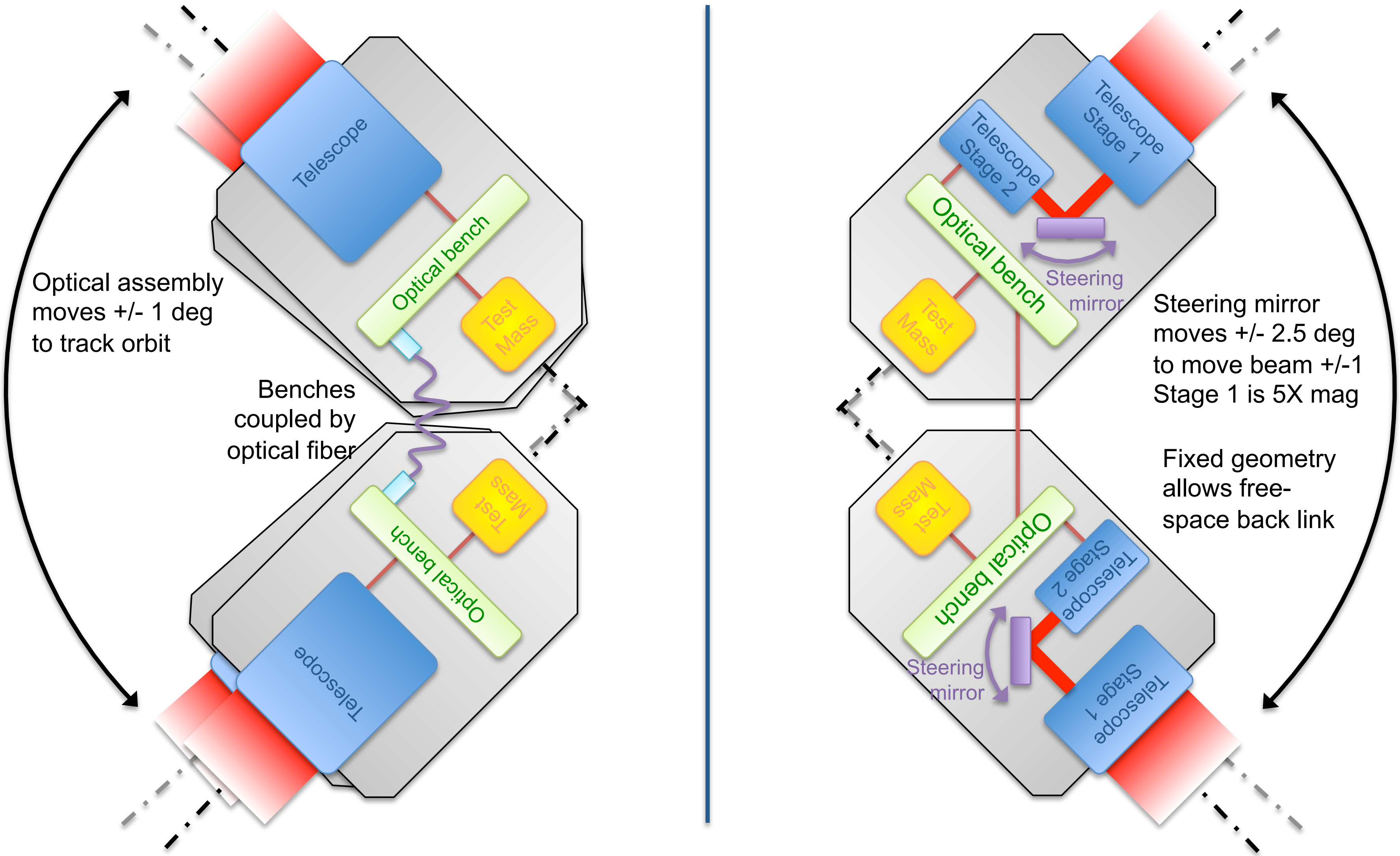
[2]UK Astronomy Technology Centre, Royal Observatory Edinburgh

Related work: C. Brugger (B2), E. Fitzsimons (B7), S. Sankar (B30) and H. Loughlin (B18)

Problem Statement

- **The triangular geometry of a LISA-like constellation changes over the course of an orbit**
- **the line-of-sight pointing of the telescope varies by an amount that depends on the orbit and the armlength**
  - For eLISA, +/- 0.6 degree is a reasonable value
  - May be able to reduce to +/- 0.1 degree (Bender: periodic thrusting)
- **The variation requires some form of compensation**
- **Two solutions proposed so far:**
  - Articulate the entire optical assembly (telescope + GRS + optical bench)
  - Make a wide FOV telescope and add a moveable mirror (In-Field Pointing)
  - Requires a 2-stage design because angular motion is magnified through the telescope and it is difficult to make a mirror with large angular motion and minimal piston
- **Scattered light forces an off-axis design**

Moving Optical Assembly vs. In-field Pointing



Moving Optical Assembly vs. In-field Pointing: System Considerations

	Articulating Assembly	In-field Pointing[1]
Telescope	Narrow FOV (+/- 200 μrad) Beam path fixed through telescope	Wide FOV (+/- 1 deg) Beam path varies[2], 2-stage design required with scanning mirror
Optical Bench	Two moving benches required	Fixed bench, possible single bench
Back Link	Fiber or steered free-space	Fixed free-space link possible
Pros	Simpler telescope design, less scattered light	Simpler SC structure, can avoid fiber back link
Cons	“large” mechanism to move assembly, impact on structure, etc. More complex back link	More difficult telescope design: more optics

Key Message: Telescope designs are very different.

[1]Related work: “An Experiment to Test In-Field Pointing for eLISA”, Brugger, C., et al., In *Proc. 10th ICSO*, Tenerife, Spain (2014).

[2]Study of pathlength noise from beam motion on mirrors: Koegel, et al., *Appl. Opt.* **52** (15) (2013).

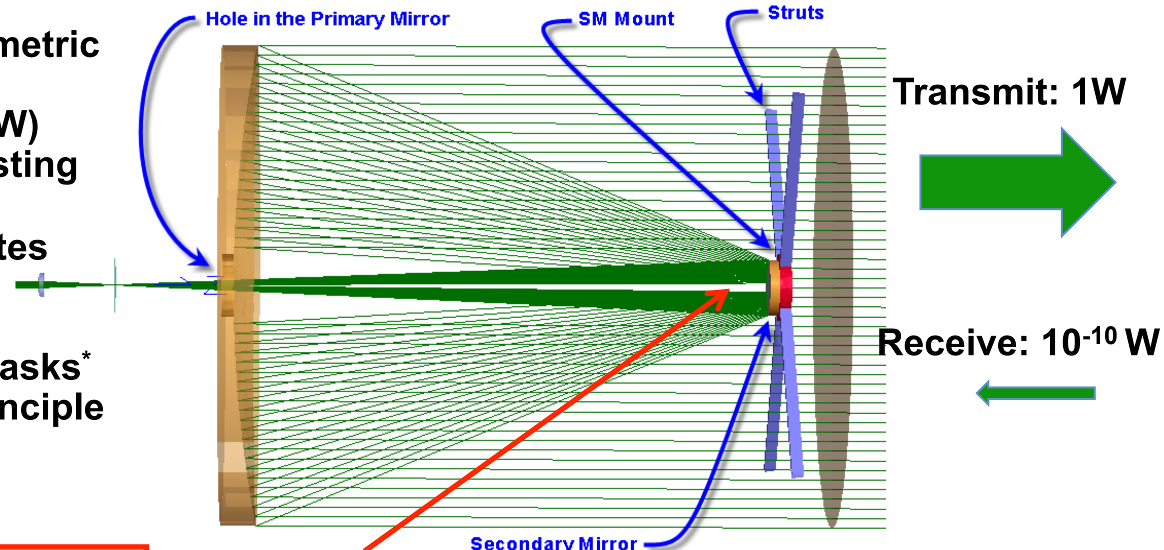
Off-axis Design Forced by Scattering

***Key challenge*:**

- **Simultaneous transmit and receive telescope operation plus an interferometric detection scheme:**
  - **combines extreme sensitivity (1 pW)**
  - **With high dynamic range of coexisting optical powers (~ 10^{10})**
- **On-axis (Narcissus) reflection dominates**
- **Hole yields on-axis Poisson spot**
- **Petaled masks suppress on-axis spot**
- **Spector and Mueller explored spiral masks***
- **Grey-scale masks may do better in principle**
- **Currently limited by**
  - **Fabrication errors/defects**

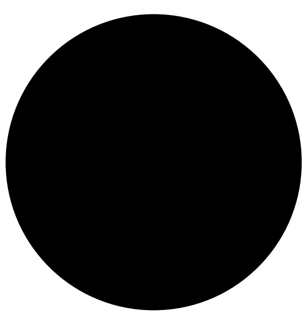
- **To date, mask performance is not good enough: must use off-axis design**

On-axis Telescope Model

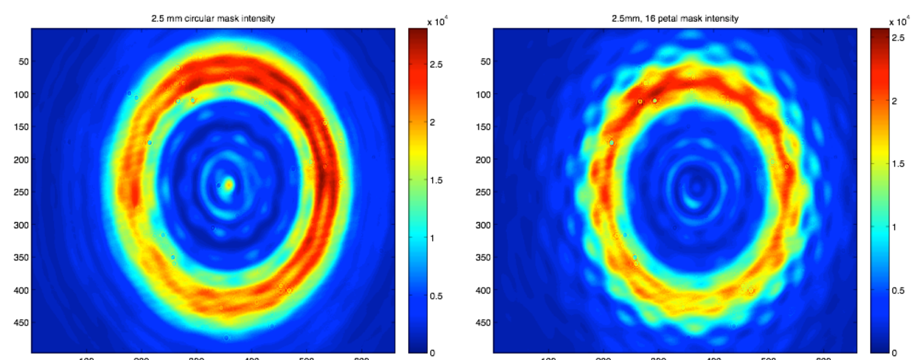


On-axis (Narcissus) secondary reflection

Circular mask/hole



Intensity Suppression Using 16-petal Mask



16-petal mask

*Spector A, PhD Thesis, UF 2015

Scattered Light Modeling: (1/4)
What we did: Telescope Design and Assumptions

- **Telescope Design**
  - Afocal: 200 mm aperture to 2.2 mm aperture (~ 90X magnification)
  - Real pupil at both apertures
  - 8 µrad instantaneous science field of view (FOV)
  - Assumed a TNO-like IFP mirror +/- 2.5 deg, first stage 5X mag, 22.5 deg angle of incidence
- **Simplified Scattered Light spec**
  - Criterion is 100 pW (10^{-10} W) into 8 µrad x 90 = 720 µrad at the detector
  - Use FRED[1] to calculate power per solid angle in small beam space
  - Simplified version of the "real" spec: Match residual phase noise in a mode that overlaps with the LO[2]
  - Specification also depends on the phase stability of the scattered light (which depends on the dimensional stability of the telescope)
- **Further analysis to include**
  - Baffling and structure
  - Multiple scattering (estimate to be very small)

[1]Photon Engineering http://photonengr.com/

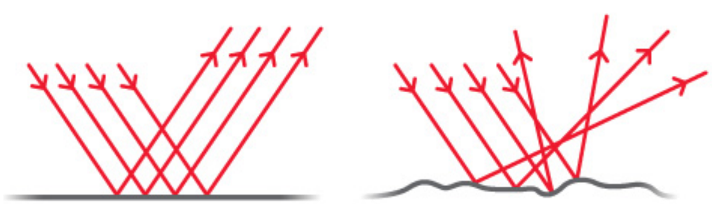
[2]Spector A, Mueller G, 2012 Class. Quantum Grav. **29** 205005

Scattered Light Modeling: (2/4) Mirror Parameters considered

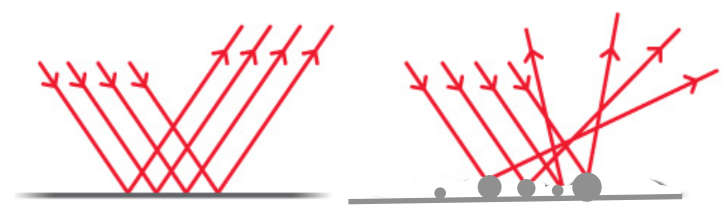
- **Surface Roughness**
  - Simple Lambertian model
  - Two levels considered
    - 5 Å RMS
    - 15 Å RMS
    - State of the art is < 1Å RMS (for a flat)
  - Some control during fabrication
  - achievable roughness depends on mirror design and fabrication technique

- **Particulate contamination**
  - “Cleanliness levels” MILSTD 1246c
  - Two levels considered
    - 200 and 300
  - Achievable on-orbit? (~ 600?)
  - Some control may be possible
    - isolate small optics and keep them cleaner than large optics

- **Typically 20/80% roughness/ particulate contribution**
  - Looser fabrication requirements lower the cost of the mirrors
  - Need to figure out how to keep the mirrors clean during I&T and on-orbit

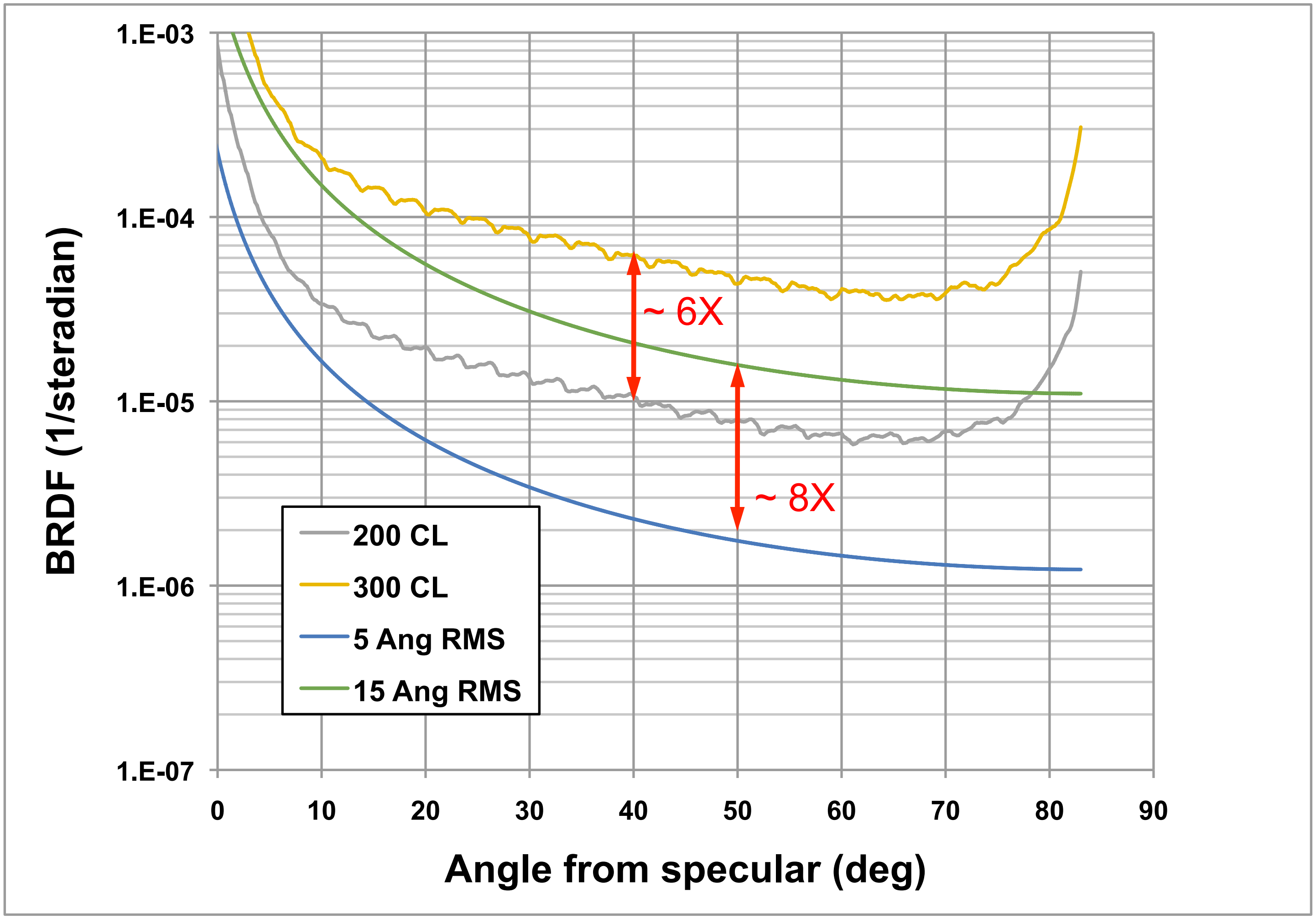


A rough surface acts as a random grating and scatters light in all directions

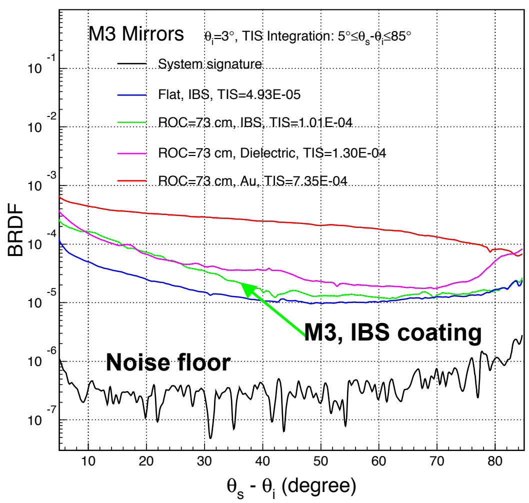


A dirty surface scatters light in all directions

Scattered Light Modeling: (3/4)
Mirror Parameters

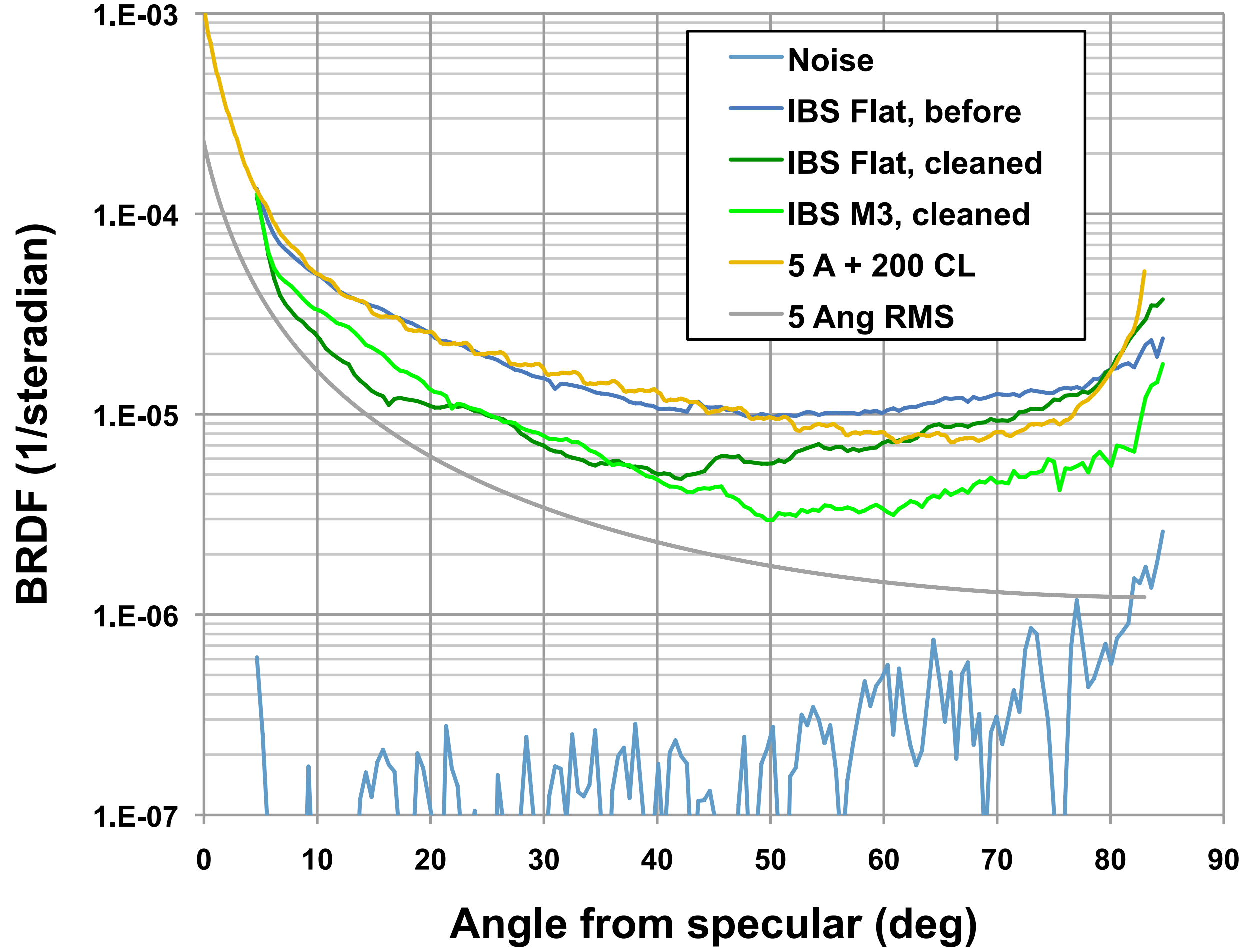


Scattered Light Modeling: Mirror measurements



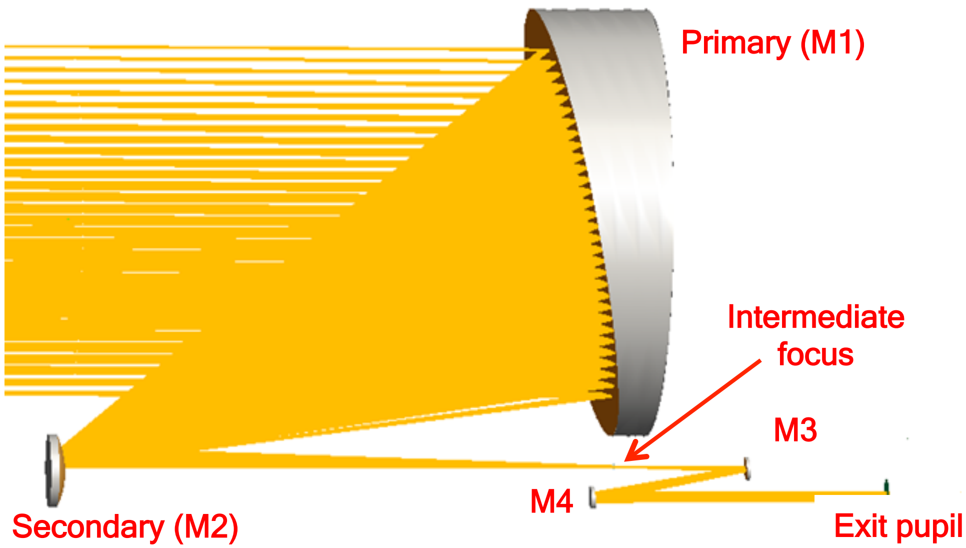
IBS Coating is best

Lab Measurements consistent with models

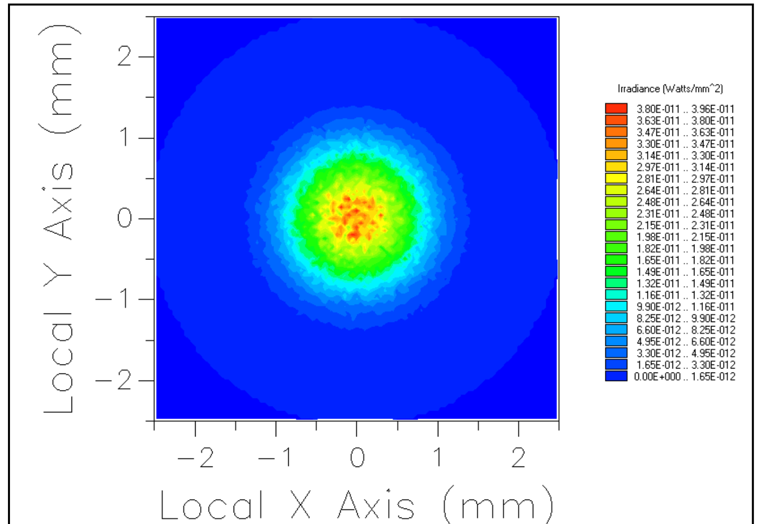


(Courtesy of G. Billingsley and L. Zhang, LIGO Caltech)

Fixed Mirror Scattered Light Analysis



Pupil Plane Scatter Irradiance



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

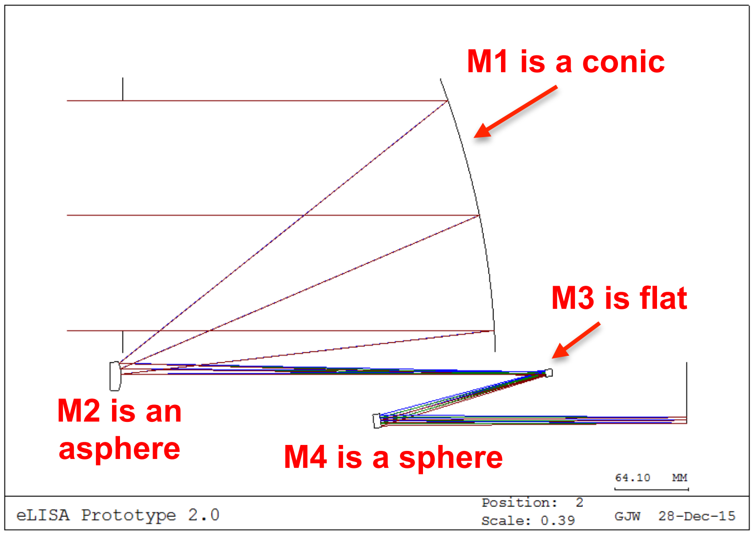
- Source power = 1W
- Total power on the detector = 6.6×10^{-11} W → (barely) meets specification of less than 10^{-10}

	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	

aft optics contributes most of the scattered light: in-field pointing needs more

Fixed Mirror Redesign for 90x

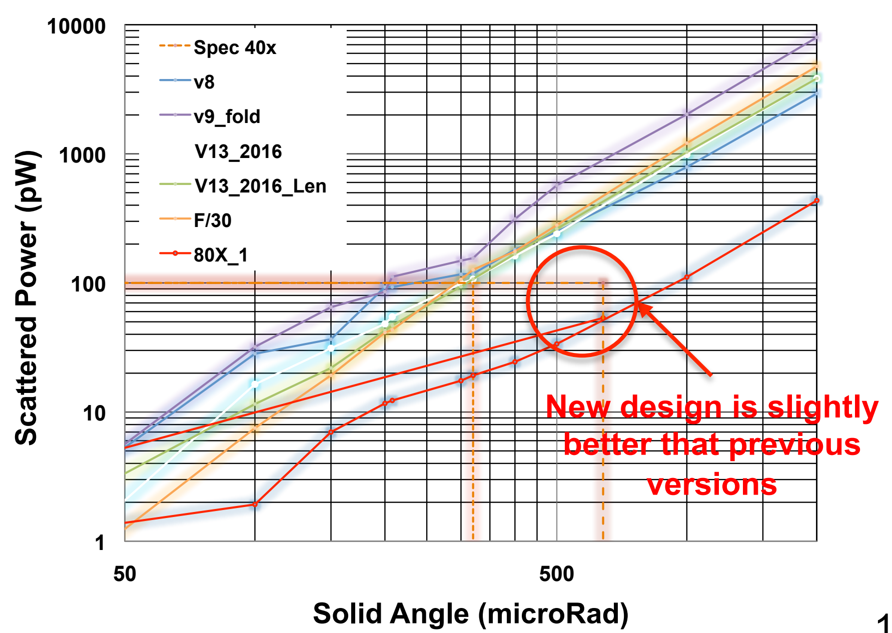
New Optical Design



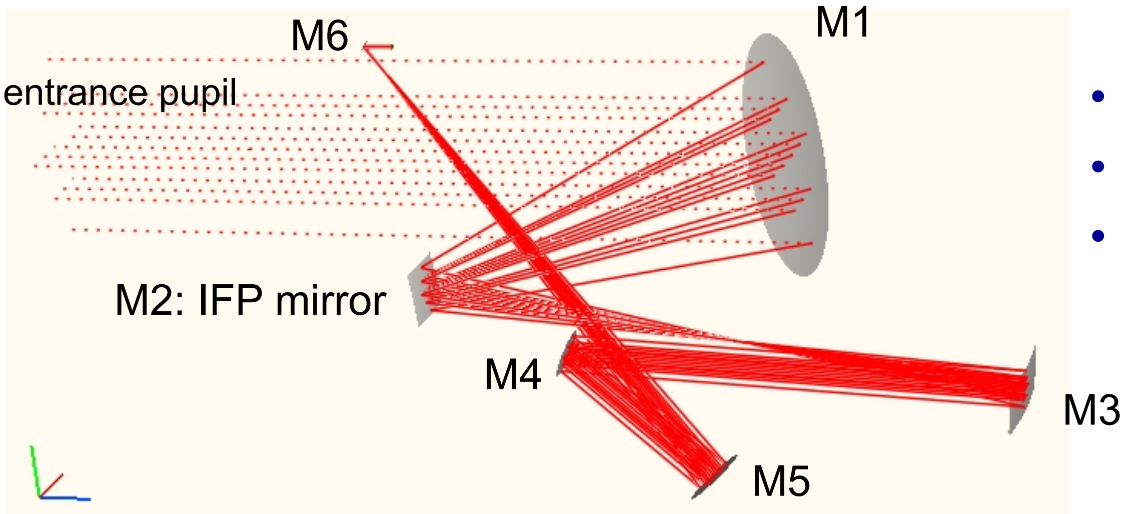
- **200 mm to 2.2 mm afocal**
  - Make M3 a flat
  - Two levels considered
    - Does not focus light
    - Can be super-polished

- **Meets Spec**
  - M1, M2 = 15 Å, 300 CL
  - M3, M4 = 5 Å, 200 CL

Scattered Light Comparison



IFP Design: minimum mirror count



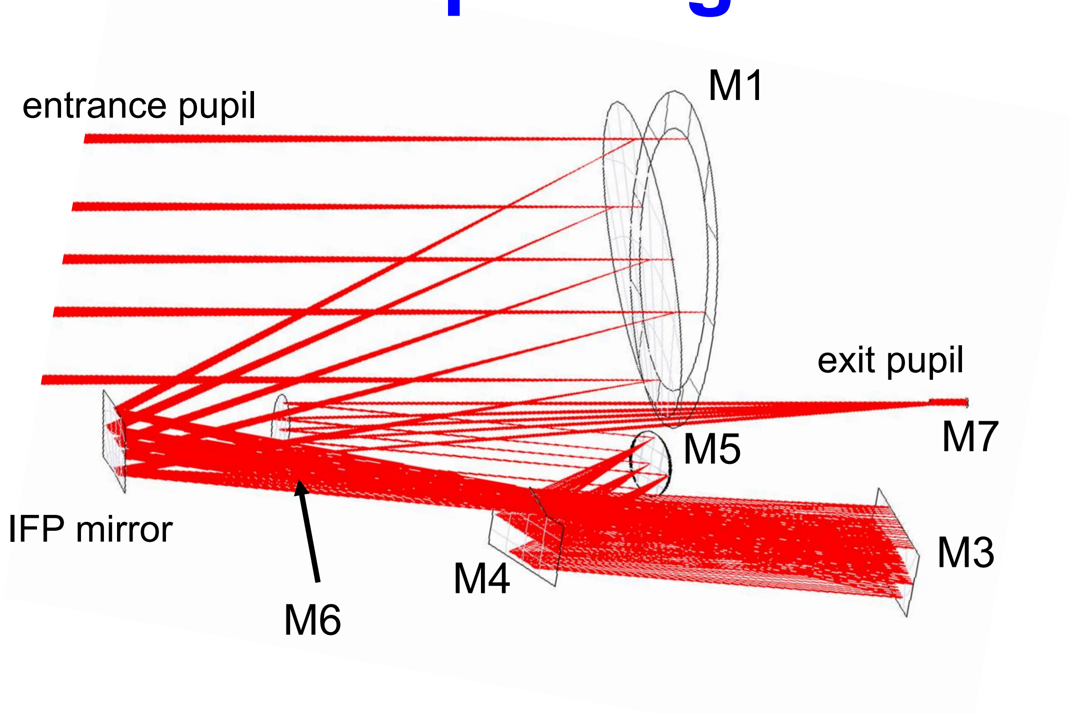
- **Minimum mirror count (6)**
- **5X magnification to M3**
- **Packaging is unrealistic**
  - **Pupil position is poor**
  - **Poor beam clearances**

- **Nominally meets spec with CL 300**
- **Most of the scattering is from M5**

Scatterers	Rays	Power (W in 720 μrad)	RMS surf rough (Å)	CL
All	83	1.2e-11	5	200
All	83	6.7e-11	5	300
M5	83	6.6e-11	5	300

Must be < 1e-10

IFP-2 Re-packaged

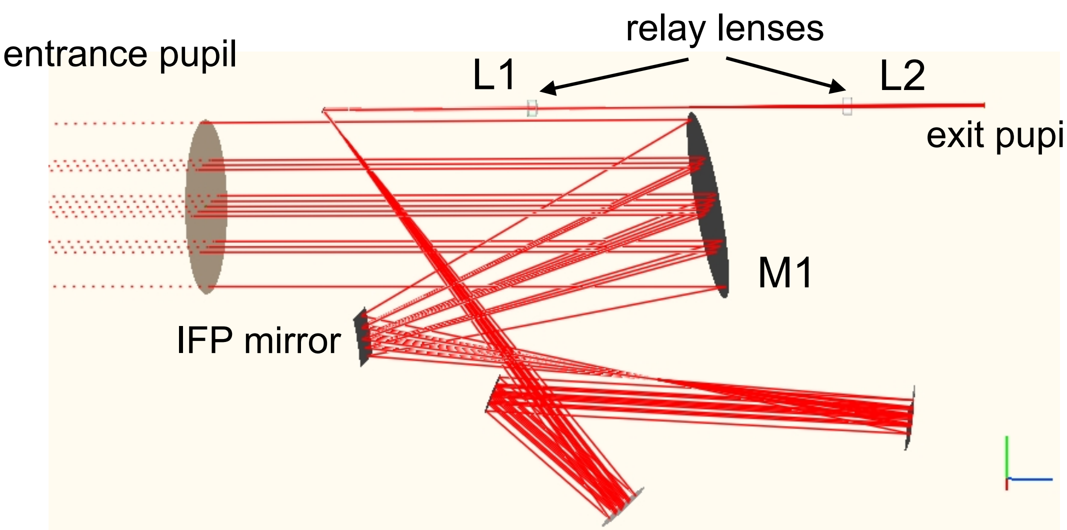


- **Re-packaged**
- **7 mirrors**
- **Better, but still poor, exit pupil position**
- **Poor beam clearances**

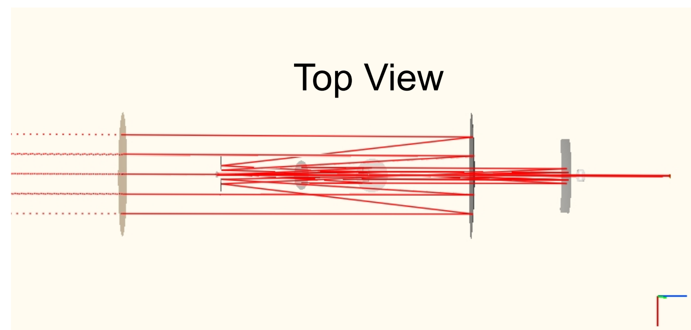
- **Only meets spec with perfect final mirror**

Scatterers	Rays	Power (W in 720 μrad)	RMS surf rough (Å)	CL
All	544	1.3e-9	5	200
All except final mirror	44	1.8e-12	5	200

IFP Design with Relay Lens Pair



- **With relay lenses**
- **6 mirrors + 2 lenses**
- **Better beam/mirror clearances**



- **Only meets spec with perfect final mirror**

Scatterers	Rays	Power (W in 720 μrad)	RMS surf rough (Å)	CL
All, 10^{-4} AR	38,633	6.8e-7	5	200
All, perfect AR	38,358	1.2e-7	5	200
All, perfect AR, no L2	216	1.7e-11	5	200

Summary

- **Minimum mirror count (poor package)**
  - 1.2e-11 with 5, 200 Meets spec
- **Repackaged no relay (better package)**
  - 1.3e-9 with all, 5, 200 Does NOT Meet spec
  - 1.8e-12 without M14 (last mirror) Meets spec with perfect mirror
- **With relay lenses**
  - 6.8e-7 with realistic (10^{-4}) AR, 5, 200
  - 1.2e-7 with perfect AR (100% transmission), 5, 200
  - 1.7e-11 with perfect AR and no scatter on the final lenses Meets spec with perfect lenses
- **Implication: scattered light must be considered in the design**
  - Have shown only that some IFP designs do not meet “spec” – NOT that they *cannot*
- **Next Steps:**
  - Agree on a design and specs
  - Optimize

Conclusion

- **In-Field Pointing implementation may be difficult for stray light**
  - (There may be other reasons to favor one approach over another)
- **Scattered Light requirement forces off-axis design**
  - Narcissus reflection from the secondary is too large
  - Suitable mask designs may allow on-axis designs but need work
- **In-Field Pointing mechanism forces a two-stage design**
  - Initial ~ 5X magnification stage
  - Final relay stage adds at least one mirror over fixed design
  - Most of scattered light likely comes from the relay stage
    - More mirrors means more scatter
  - Lateral beam motion on the mirrors before the moveable mirror prevents careful baffling before moveable mirror
    - May have stray light issues in addition to scattered light issues
    - Scattering depends on the angle of incidence in the front end optics
    - Scattering depends on the angle of incidence with the moveable mirror

Backup Material

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	$\leqq$ λ/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)
challenging	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
challenging	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

Scattered Light Modeling: Particulate Contamination

MILSTD 1246c

Level	Size (µm)	Count/ft²	Count/m²	Count per liter
200	15	4189	4520	41890
	25	1240	1340	12400
	50	78	84.2	1700
	100	16	17.3	160
	200	1.08	10	1
300	25	7455	8050	74550
	50	1021	1100	10210
	100	95	103	950
	250	2.3	2.48	23
	300	1	1.08	10

ISO 14644-1 (replaces 209E)

Particles/m³						
Class	**0.1 µm**	**0.2 µm**	**0.3 µm**	**0.5 µm**	**1.0 µm**	**5.0 µm**
ISO 1	10	2				
ISO 2	100	24	10	4		
ISO 3	1,000	237	102	35	8	
ISO 4	10,000	2,370	1,020	352	83	
ISO 5	100,000	23,700	10,200	3,520	832	29
ISO 6	1,000,000	237,000	102,000	35,200	8,320	293
ISO 7				352,000	83,200	2,930
ISO 8				3,520,000	832,000	29,300
ISO 9				35,200,000	8,320,000	293,000