Progress towards a high dimensional stability telescope for gravitational wave detection

Shannon Sankar

shannon.r.sankar@nasa.gov

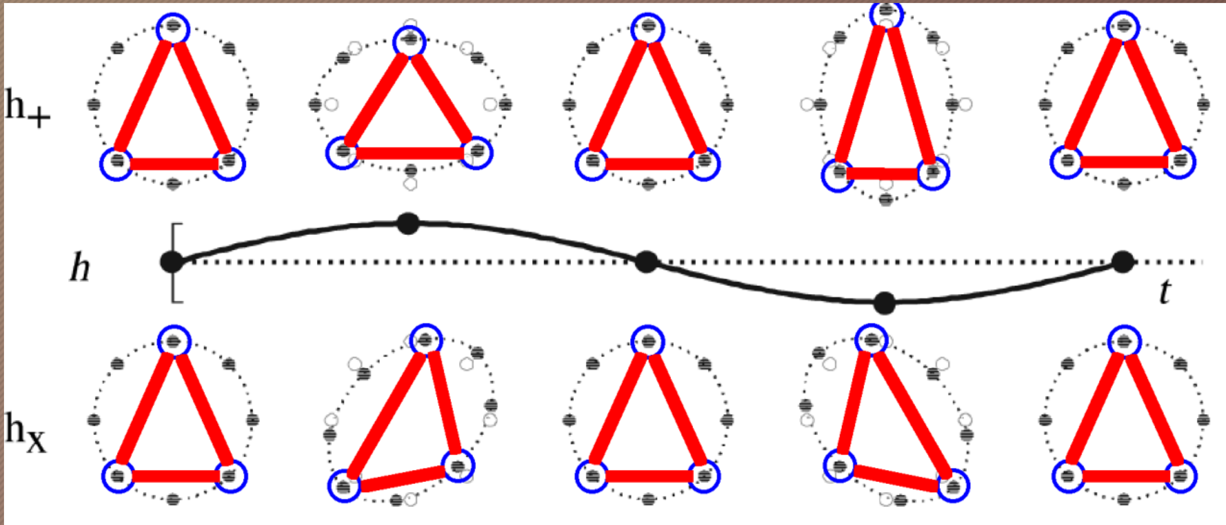
USRA/CRESST/GSFC

Jeffrey Livas (PI), Peter Blake, Joseph Howard,

Garrett West, Lenward Seals, Ron Shiri, Justin Ward

Gravitational waves

- Large accelerating compact masses
- Two polarizations
- Far field: change in proper separation between free bodies
- Very small effect measured as ΔL/L (spacetime strain).
  - Roughly 5 pm amplitude change over 5 Gm baseline between 0.1 mHz to 0.1 Hz.



Exciting times: 2015/2016

Exciting times: 2015/2016

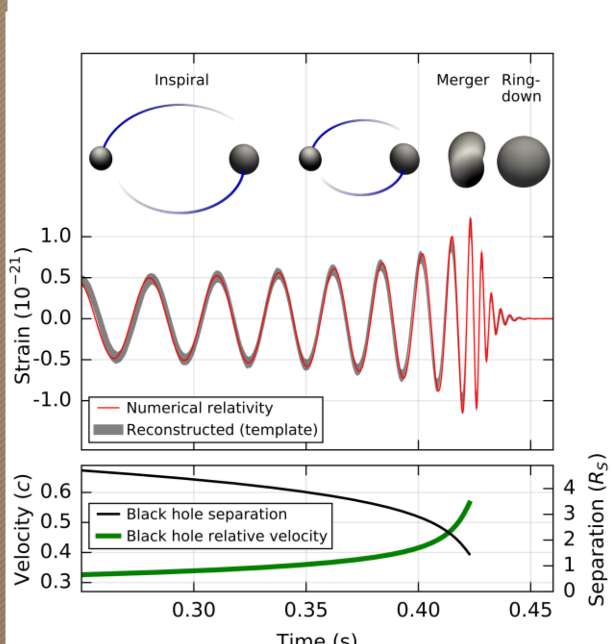
- 14th September 2015 – LIGO detects GWs from merging black holes.

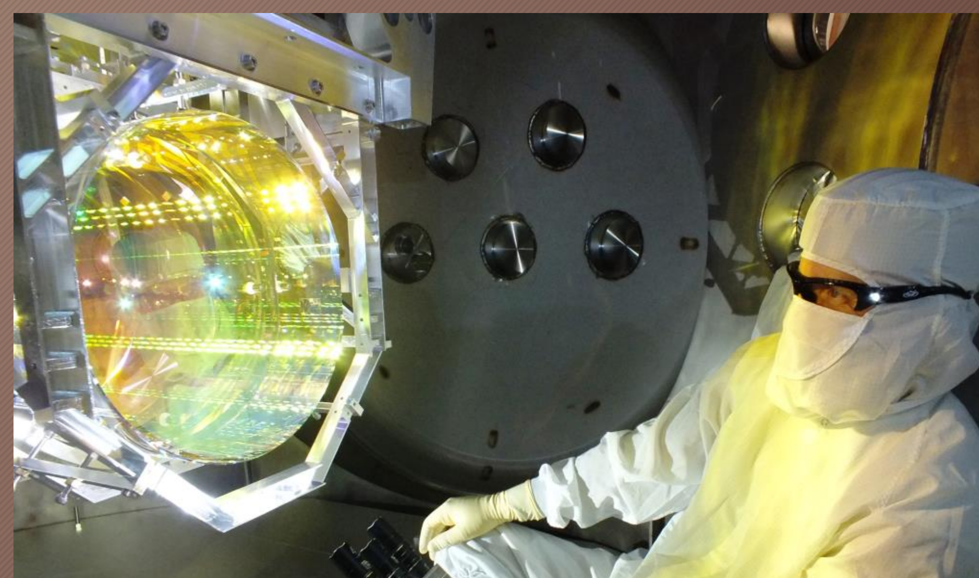
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

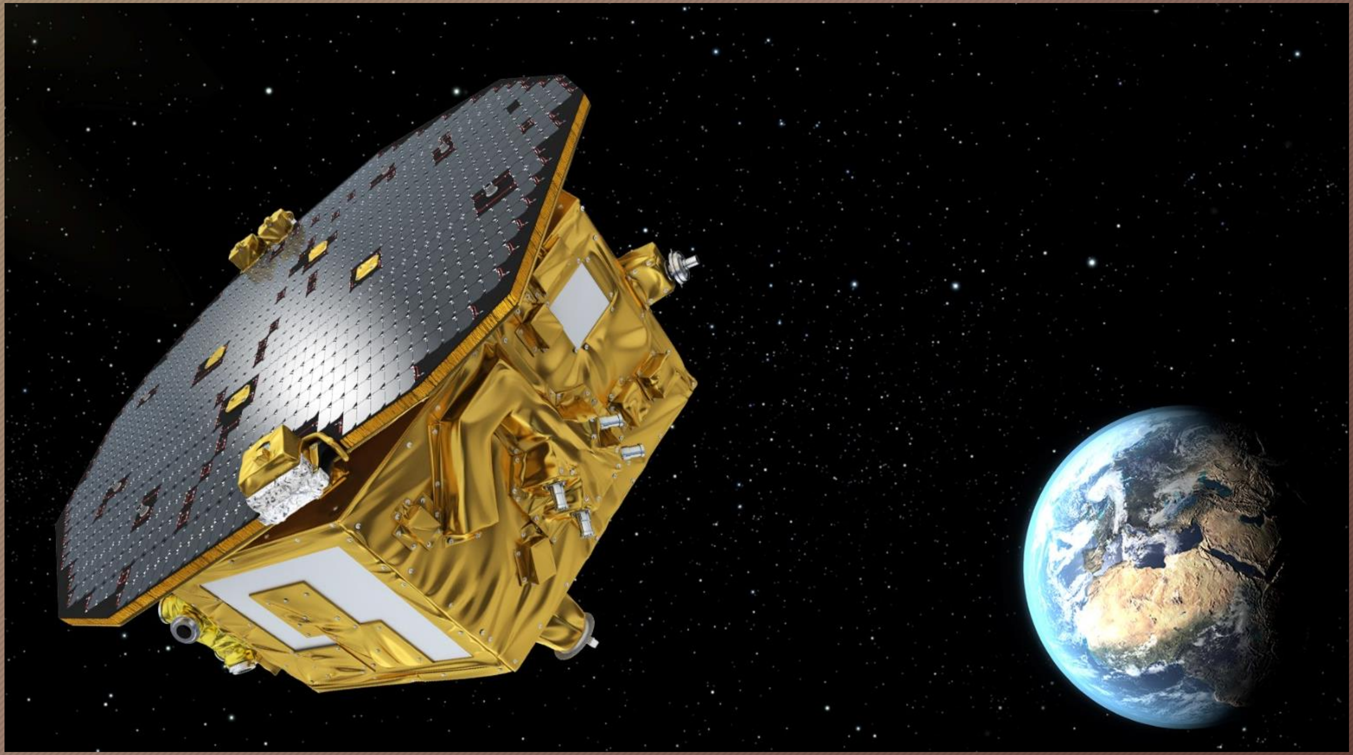
(Received 21 January 2016; published 11 February 2016)





Exciting times: 2015/2016

- 14th September 2015 – LIGO detects GWs from merging black holes.
- 03rd December 2015 – LISA Pathfinder launched by ESA.



Exciting times: 2015/2016

- 14th September 2015 – LIGO detects GWs from merging black holes.
- 03rd December 2015 – LISA Pathfinder launched.
- 26th December 2015 – LIGO detects another merger of black holes.

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

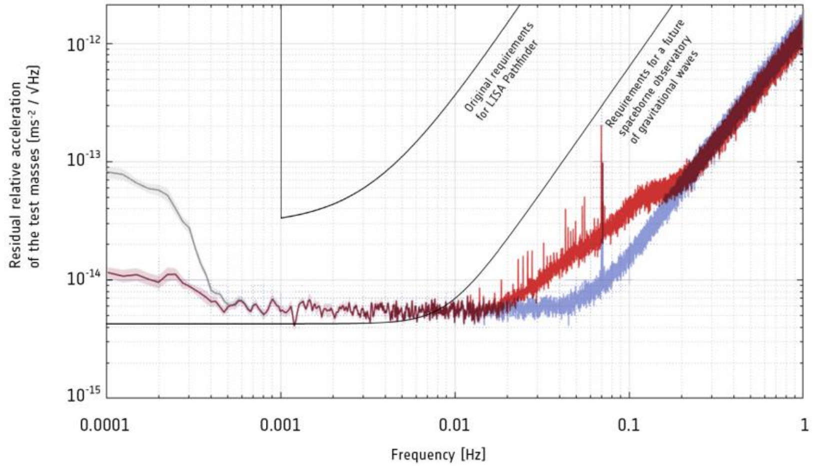
(Received 31 May 2016; published 15 June 2016)

Exciting times: 2015/2016

- 14th September 2015 – LIGO detects GWs from merging black holes.
- 03rd December 2015 – LISA Pathfinder launched.
- 26th December 2015 – LIGO detects another merger of black holes.
- 07th June 2016 – Pathfinder results public.

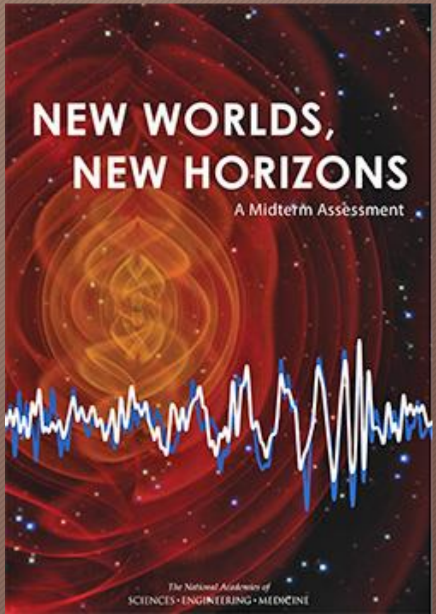
Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

(Received 4 May 2016; published 7 June 2016)



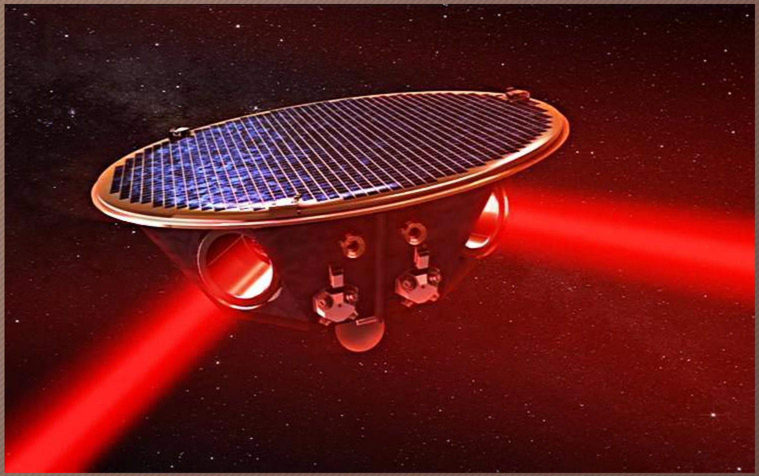
Exciting times: 2015/2016

- 14th September 2015 – LIGO detects GWs from merging black holes.
- 03rd December 2015 – LISA Pathfinder launched.
- 26th December 2015 – LIGO detects another merger of black holes.
- 07th June 2016 – Pathfinder results public.
- 15th August 2016 – Midterm Decadal Assessment report published.

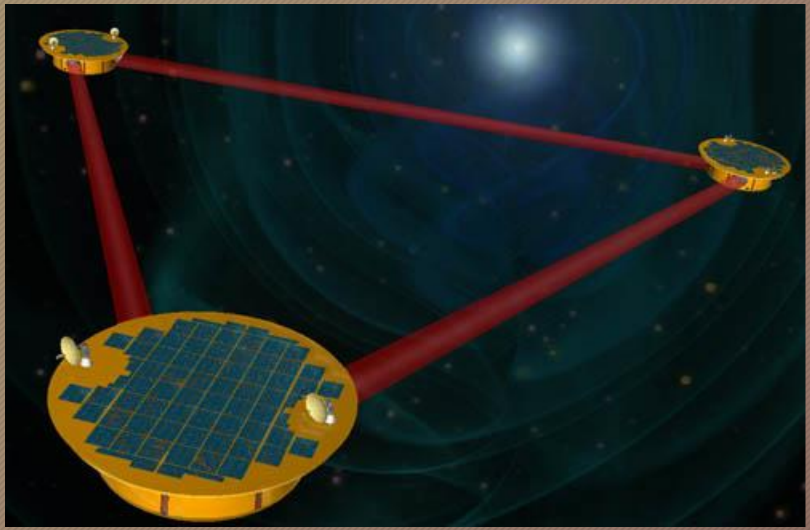


Exciting times: 2015/2016

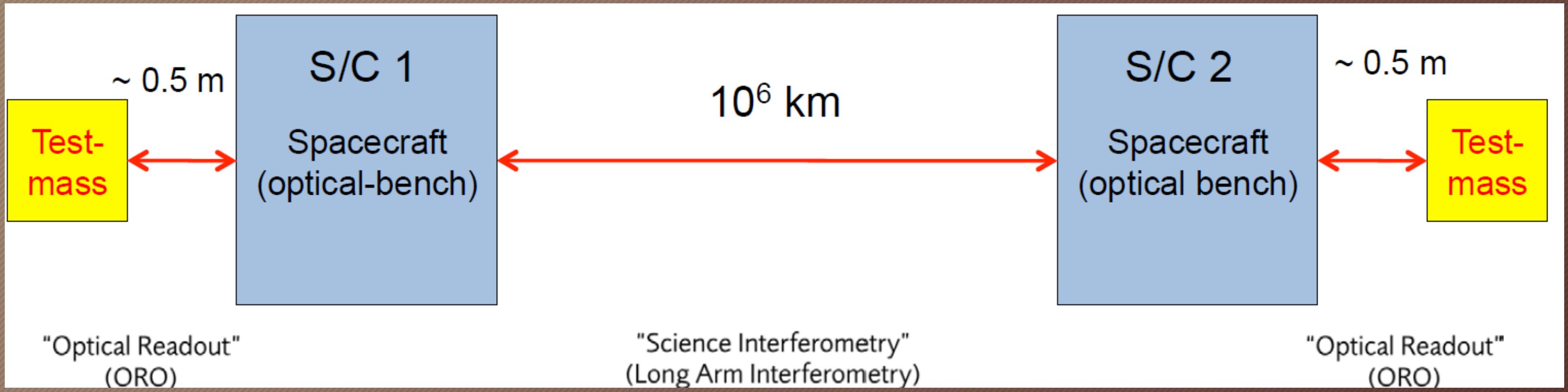
- 14th September 2015 – LIGO detects GWs from merging black holes.
- 03rd December 2015 – LISA Pathfinder launched.
- 26th December 2015 – LIGO detects another merger of black holes.
- 07th June 2016 – Pathfinder results public.
- 15th August 2016 – Midterm Decadal Assessment report published.
- 25th October 2016 – L3 Gravitational Universe Call for Missions (ESA)



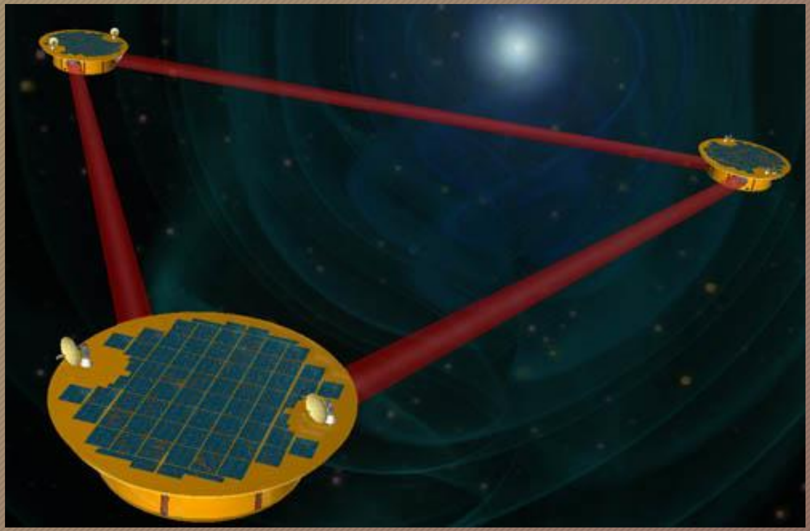
The LISA Mission



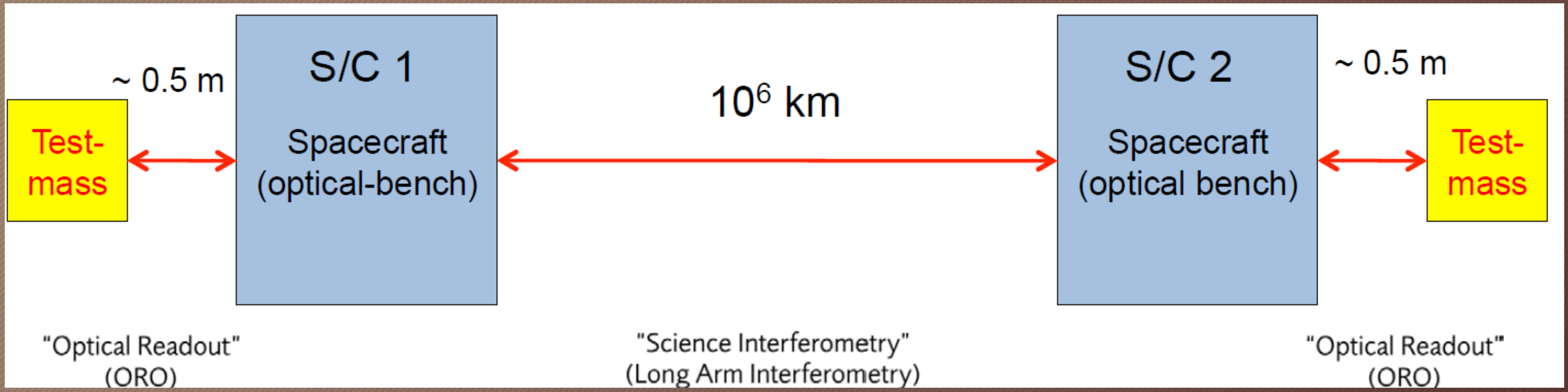
- 3 arms, 6 links
- Avoids terrestrial noise
- Two proof masses per spacecraft
- Geodesic orbits, not formation flying
- Trails Earth by about 20 degrees
- Precision heterodyne interferometry
- Post processing: TDI technique



The LISA Mission

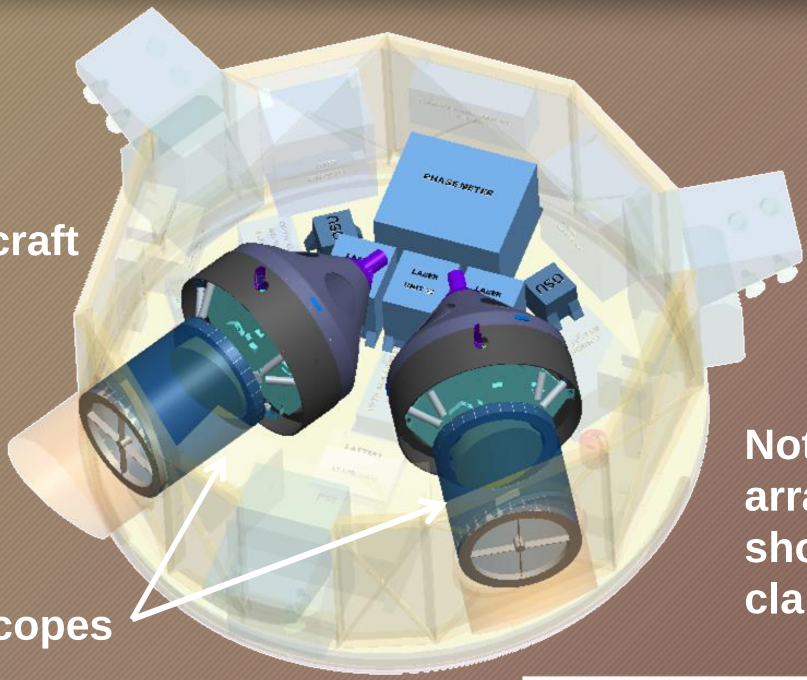


- Compact binaries
- Physics of tidal interactions
- Black hole and NS binaries and rates
- EMRIs – tests of gravity
- Double white dwarf binaries
- Guaranteed sources (verification binaries)
- Cosmic superstrings/exotic sources?



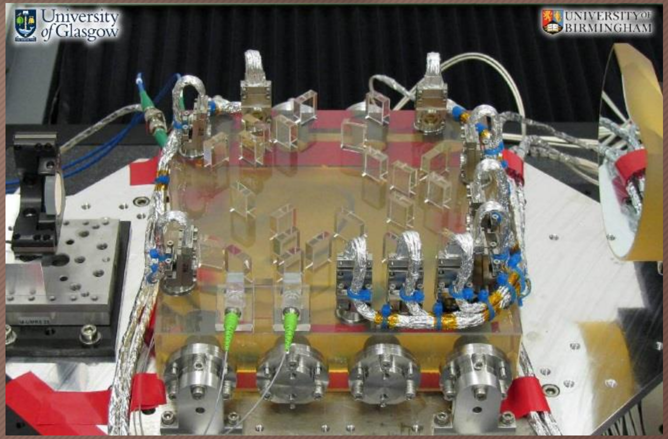
The LISA Sciencecraft

Typical Sciencecraft

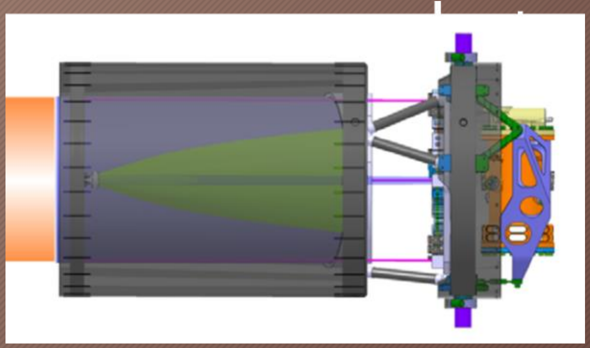


Telescopes

Note: solar array not shown for clarity.



Pathfinder optical bench (University of Glasgow)



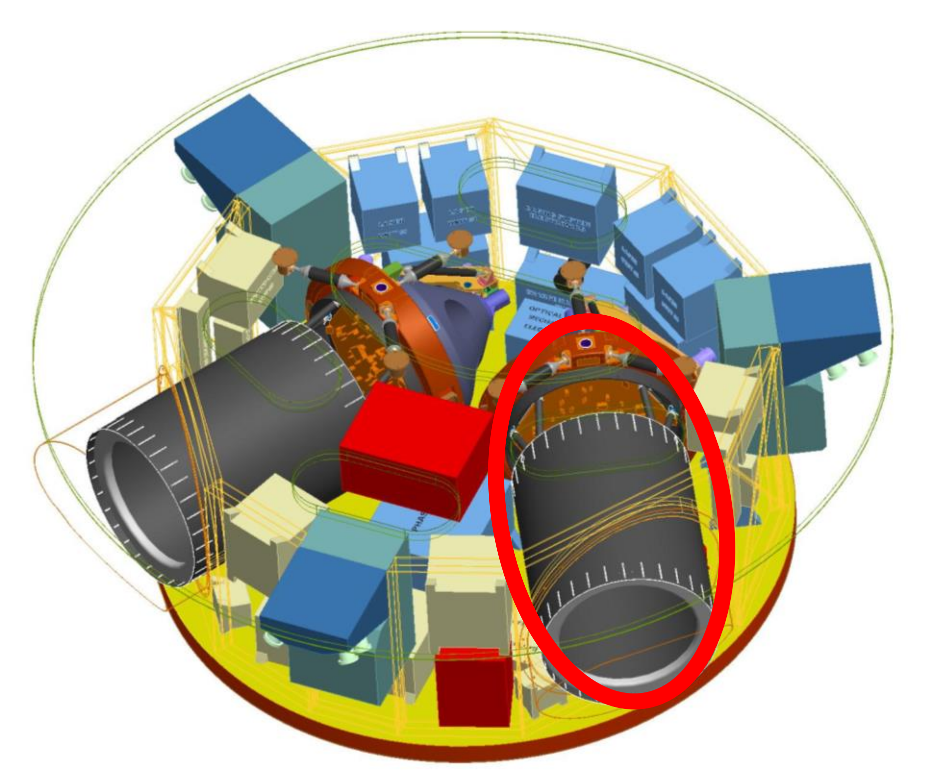
Optical assembly

- Pathlength stable
- Not for imaging

Telescope Role & Function

- Simultaneously transmit ~1 W, receive ~100 pW.
- Angle-angle coupling. Ideally no jitter-piston coupling.
- Re-focus mechanism. “Set and forget” mode.
- May need to articulate a mirror to follow breathing of the arms. “In-field Pointing”
- May also pivot the entire optical assembly. “Articulated assembly”
- Pathlength stability: must not degrade the observatory performance
- Thermal shielding (passive)
- Thermal conductivity (gradients applied)

LISA Telescope



- “Full duplex”
- Need to avoid scattering the transmitted beam into the received beam (phase noise)
- High overlap on the detector with the local reference

- About 10 telescopes needed.
  - 6 for spaceflight
  - 2 for ground tests
  - Spares/backups

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	$\leq \lambda/30$ 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

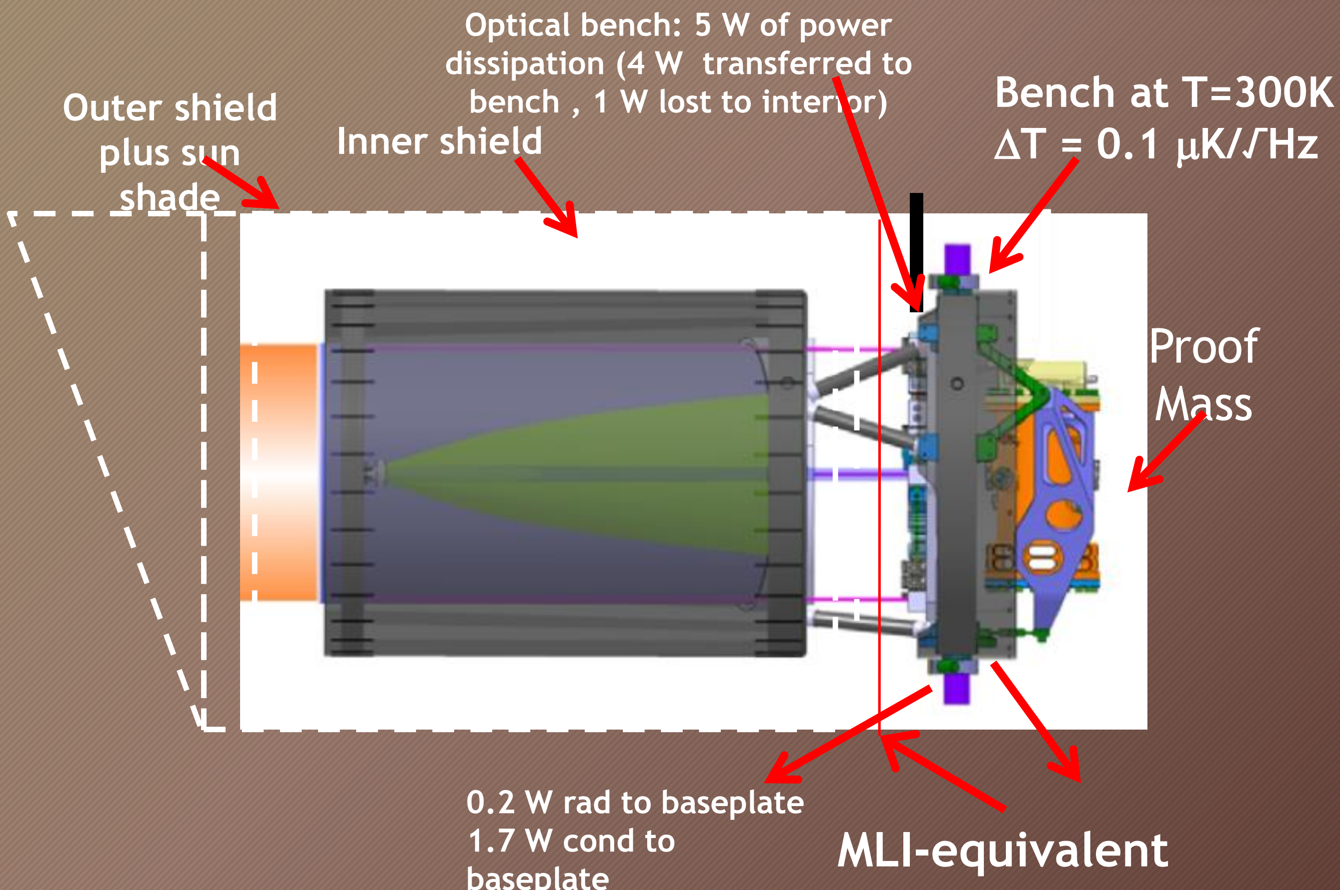
challenging (row 7)

challenging (row 11)

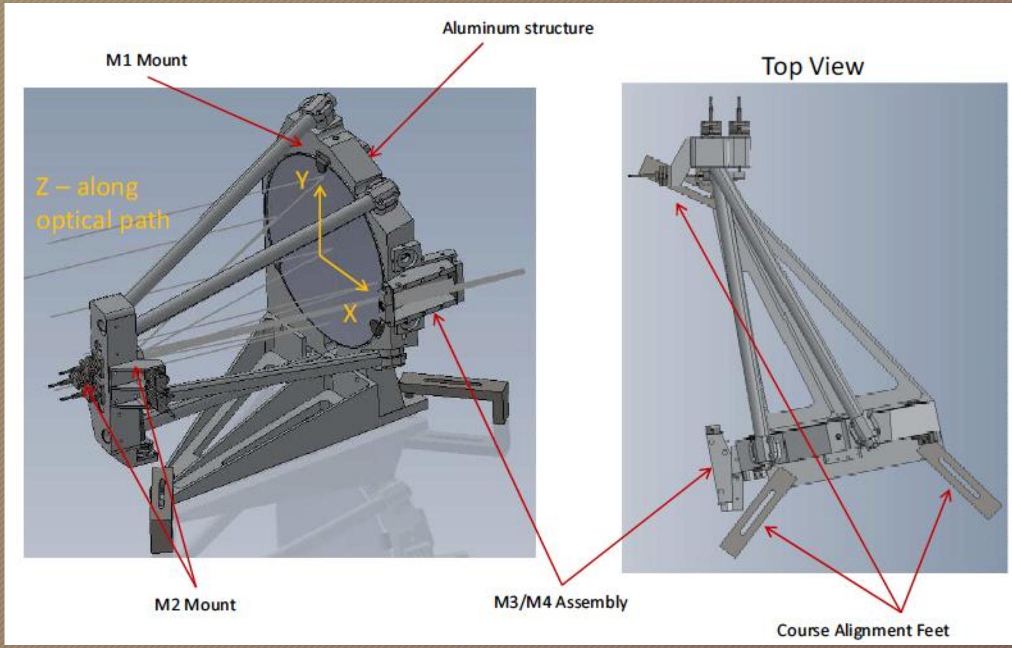
SGO-Mid = 250 mm

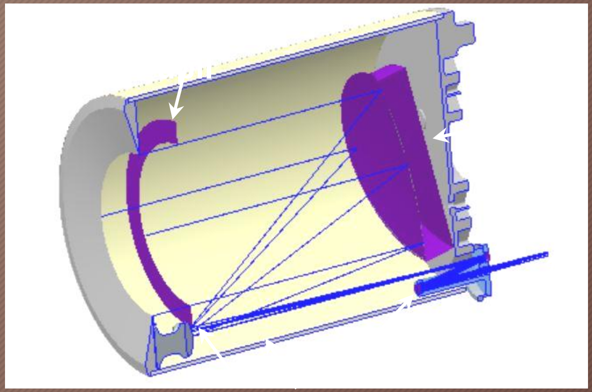
From U of Glasgow bench design, courtesy of Ewan Fitzsimons and Harry Ward

Key Interfaces



Mechanical Implementations

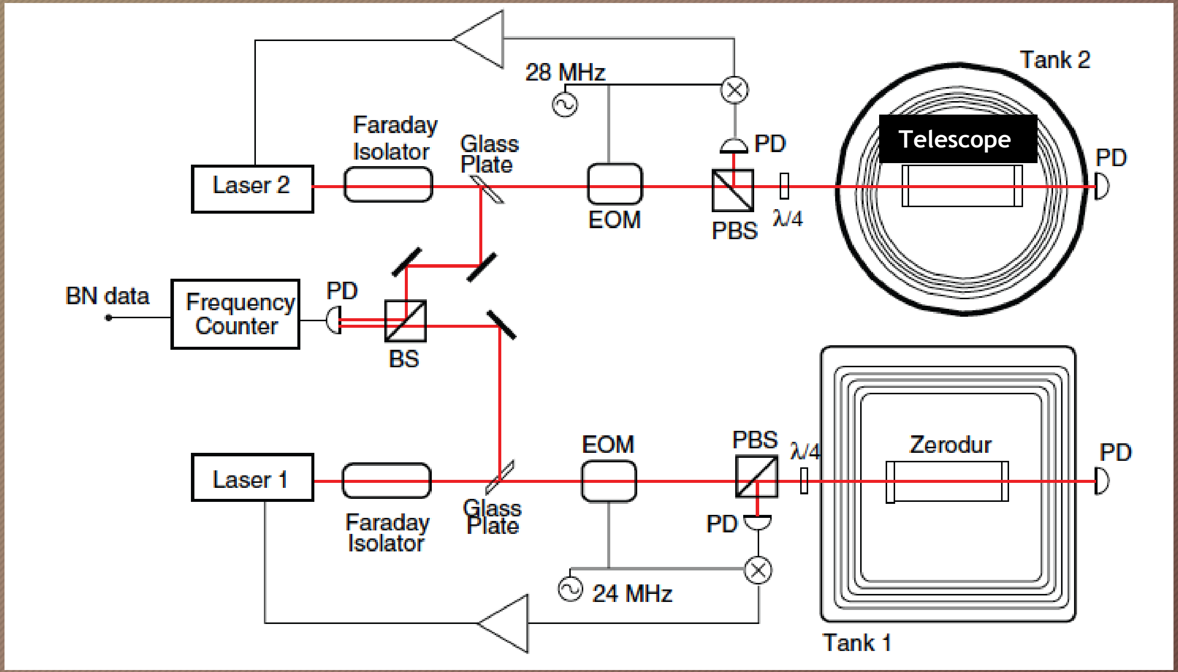




- Open to creative designs
- Off-axis
- Unobstructed, stable
- Materials exist/being developed

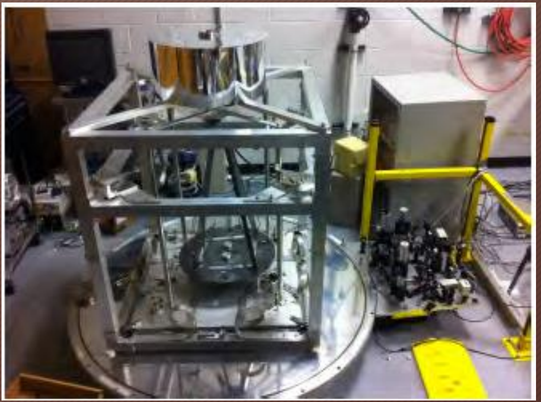
Dimensional stability testing

- University of Florida/Gainesville
  - Dimensional stability measurement
    - Large, instrumented vacuum tank used for spacer stability demonstration
    - Vibration and thermal isolation
    - Frequency stabilized laser



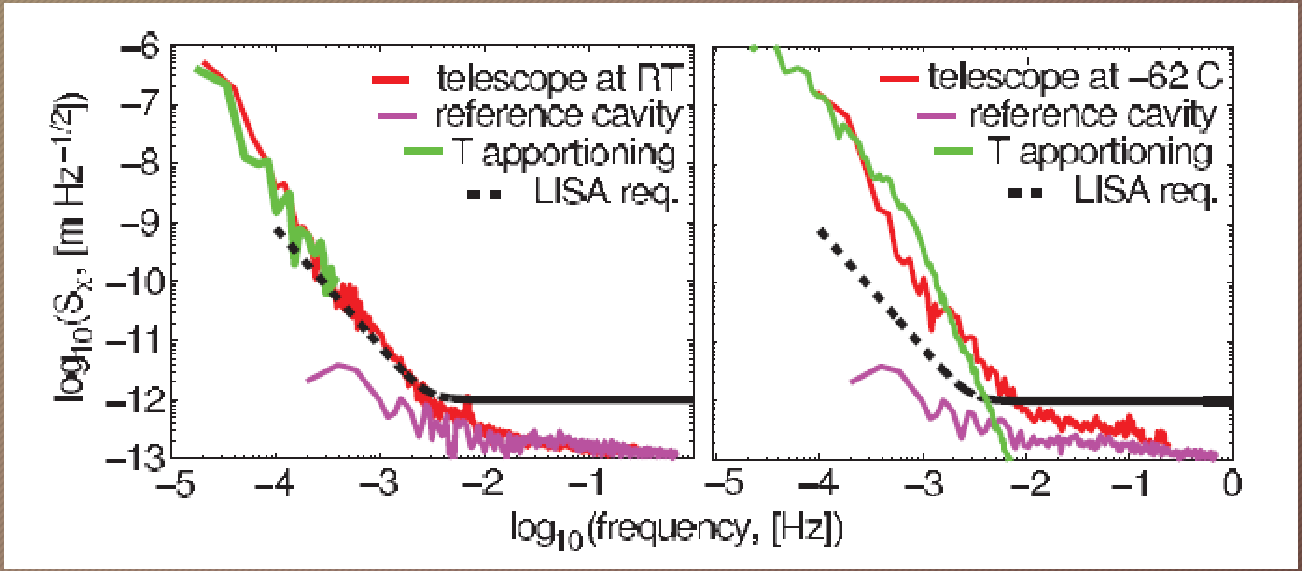

UF Test Chamber

Internal fixtures and vibration isolation



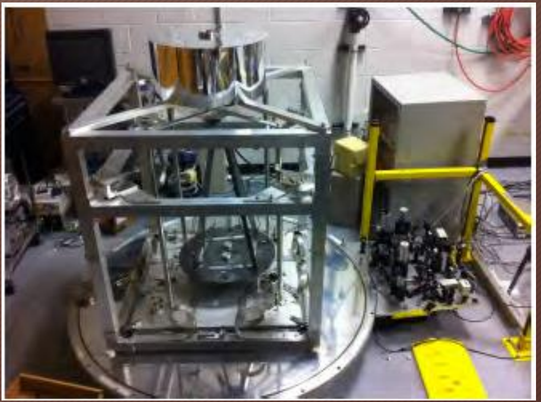
Dimensional stability testing

- University of Florida/Gainesville
  - Dimensional stability measurement
    - Large, instrumented vacuum tank used for spacer stability demonstration
    - Vibration and thermal isolation
    - Frequency stabilized laser



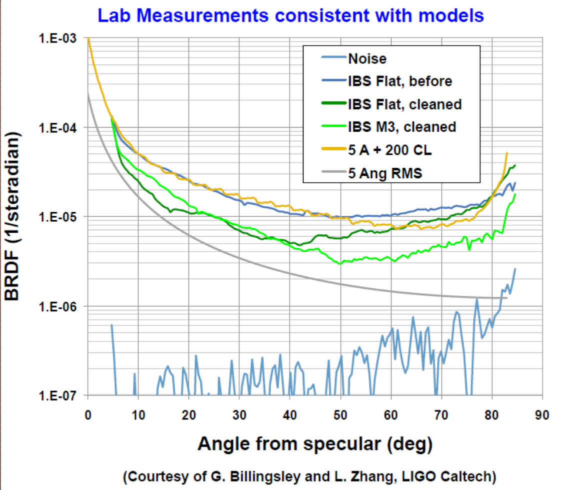

UF Test Chamber

Internal fixtures and vibration isolation



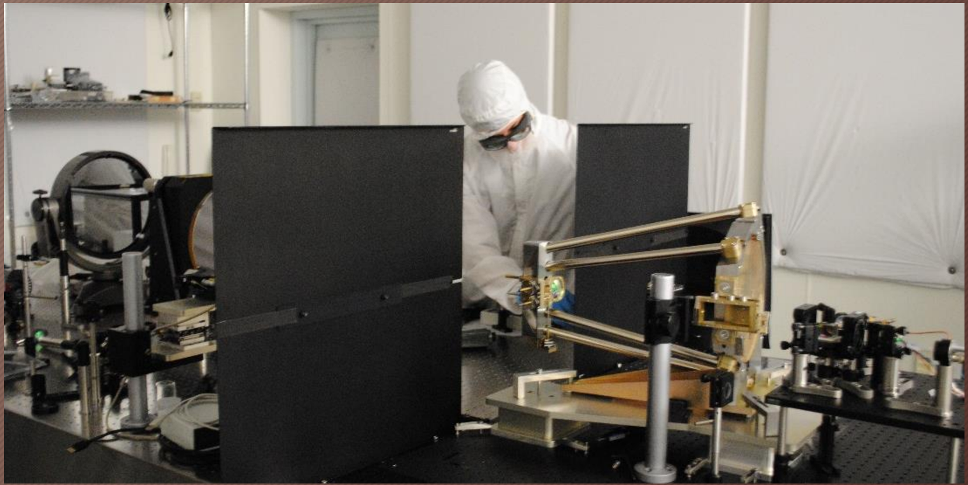
Scattered light performance

- Extensively modeled in FRED (software by Photon Engineering)
- Scatter is design-dependent. For 4-mirror designs, M3 and M4 are important.
- Roughness: 5-15 angstrom
- Cleanliness: CL 200 to CL 300 (1246-c)



Scattered light testing and model verification underway with prototype at Goddard!

Pictured: Hudson Loughlin
(Princeton, Mather scholar 2016)



Technologies used/needed

- Demonstrated stability, no creep
- Performance under applied gradients
- High conductivity, low CTE and high dimensional stability
- Low/Zero moisture coefficient of expansion
- Low magnetic susceptibility
- High specific stiffness
- Low scatter coatings
- Low surface roughness
- Repeatability/Reliability/Efficiency – multiple copies needed.

Points of Contact

- Principal investigator: Jeff Livas
  - jeffrey.livas-1@nasa.gov
- Optics lead: Garrett West
  - garrett.j.west@nasa.gov
- Presenter: Shannon Sankar
  - shannon.r.sankar@nasa.gov

- Also Joe Howard, Peter Blake, Ron Shiri here at MTD

Acknowledgement: This work supported by SAT grant (PI: Jeffrey Livas).