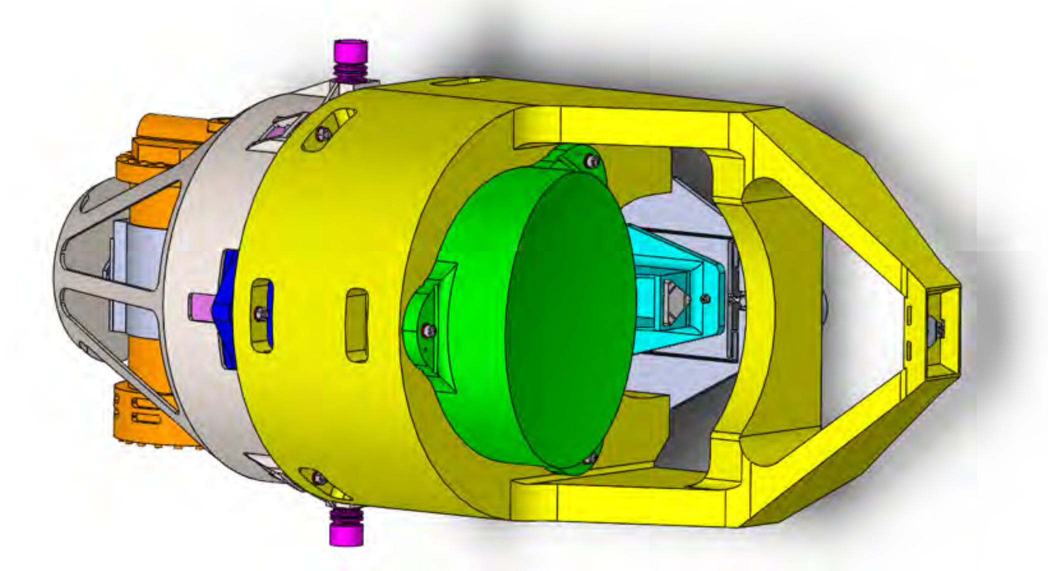
Optical Telescopes for the L3/LISA Space-Based Gravitational Wave Observatory



Jeff Livas for the US LISA Telescope Team

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Nov 2017

Telescope Team

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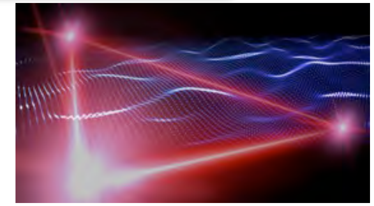

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Outline

- Mission Context and Science
- Measurement Principles
- Telescope Description
- Challenges
- Summary

MISSION CONTEXT AND SCIENCE

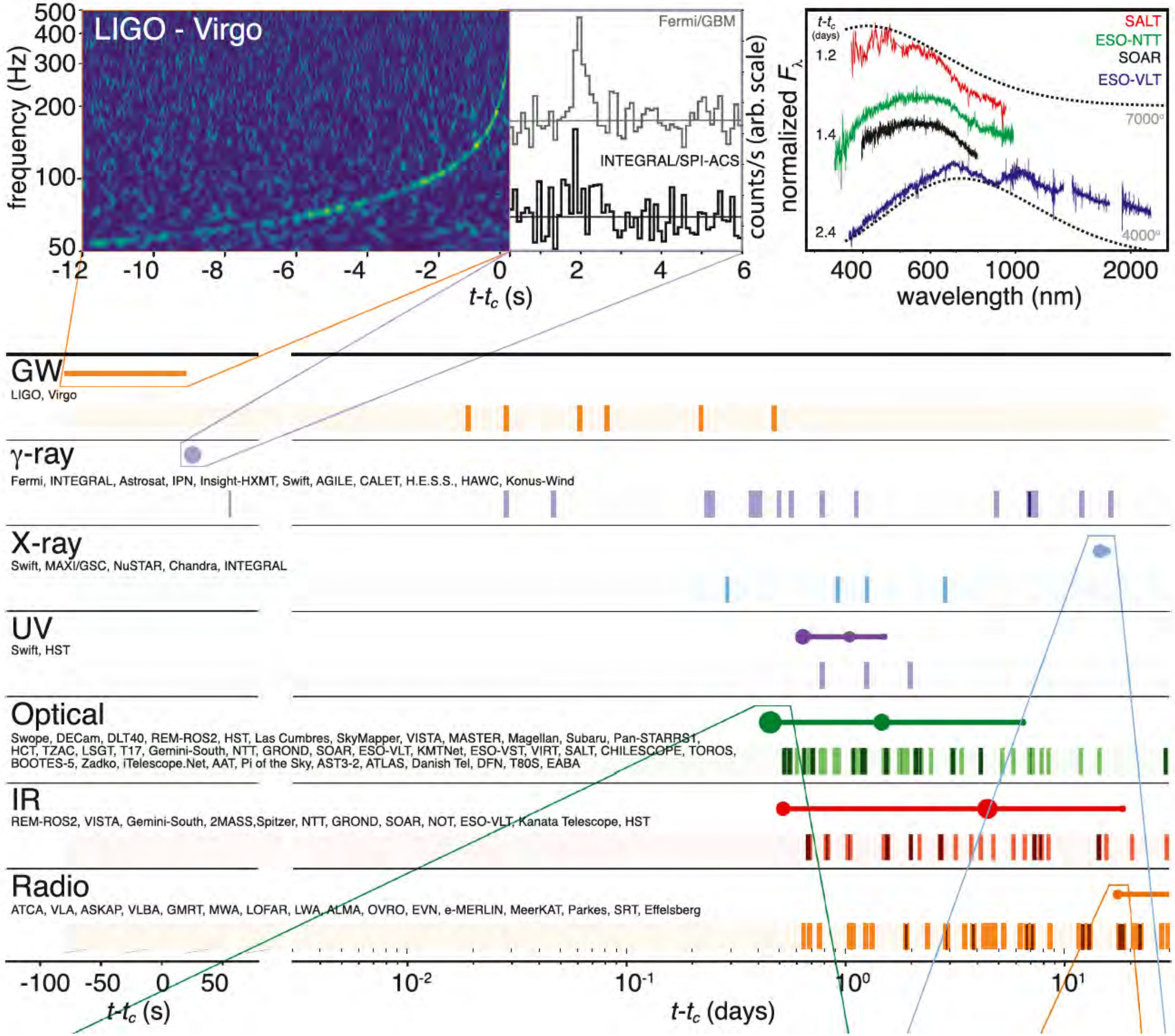
Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101



LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
normalized F_λ
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1,
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS,
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)

Why is this important?

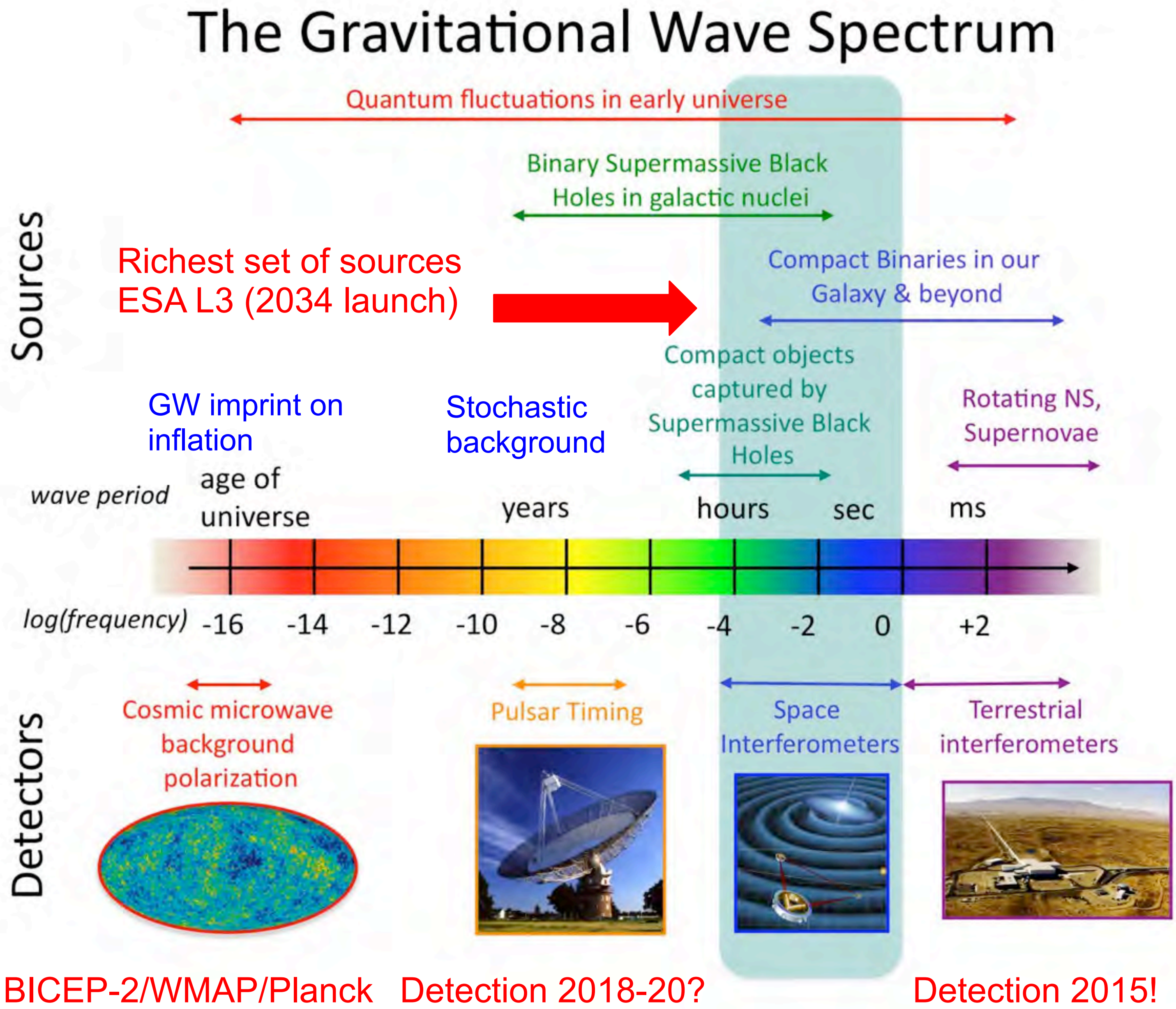
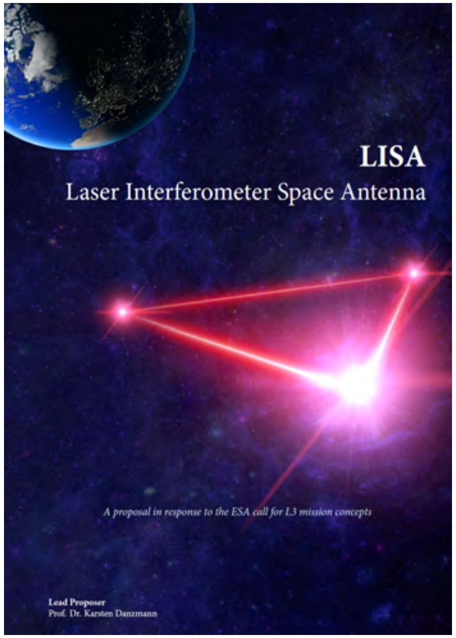


Image credit: NASA

ESA/NASA Activities

- Phase A to start early 2018:
  - Follows selection by SPC earlier this year
  - Intended to be competitive industrial study
  - 18 month duration
  - ESA Study Office has been established
  - Science Study Team has been established
  - US team also assembled to address decadal survey

  https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf



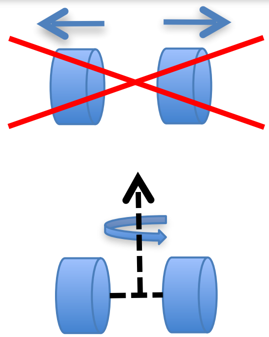
- GSFC plans:
  - Plan to produce a Breadboard by 2022
  - Currently iterating through optical/structural/thermal design
  - Other technologies also under development

  https://lisa.nasa.gov/

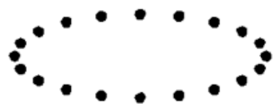
MEASUREMENT PRINCIPLES

Measurement Challenge

- Lowest order radiator is a quadrupole
  - Dipole radiation forbidden by conservation of momentum
  - Simplest quadrupole: a “dumbell”



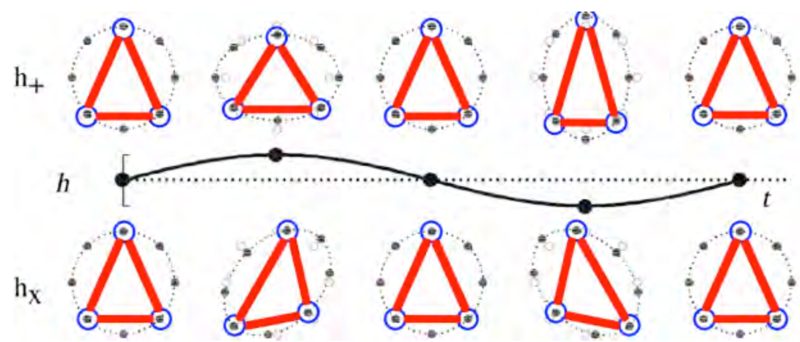
h_+ Polarization



h_x Polarization

- What is to be measured
  - Time-varying strain ($\Delta L/L$): ~**10^{-21} /√Hz**
  - 5 pm/√Hz / 5 Gm
  - signal frequencies from 10^{-4} to 1 Hz,
  - signal durations of months to centuries

Constellation Response

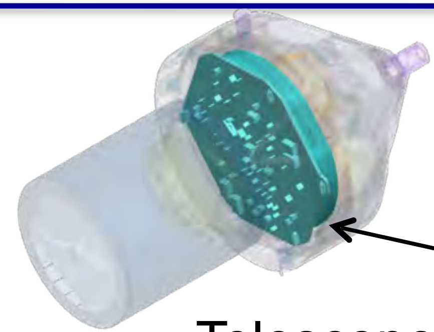


- Measurement concept
  - Measure distance changes between free-falling mirrors
  - Preferred measurement conditions:
    - A long measurement path to make ΔL large
    - A very quiet place to avoid disturbances to the test masses: SPACE!

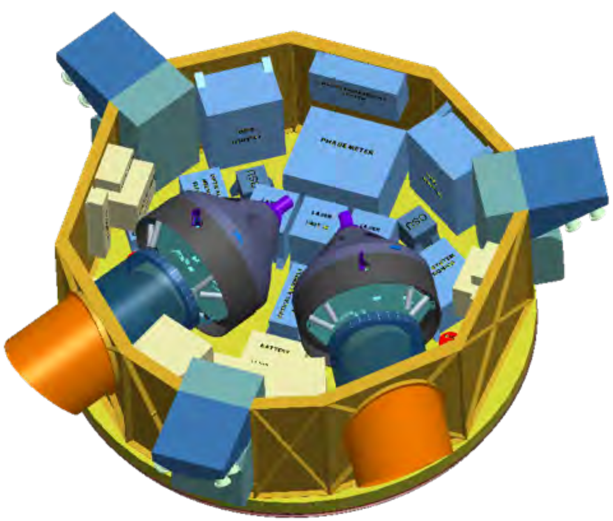
Payload Integrated with Bus

Payload systems

- Interferometer Measurement System (IMS)
  - Laser
  - Telescope
  - Optical bench
- Disturbance Reduction System (DRS)
  - Gravitational Reference Sensor (GRS)
  - μN thrusters
  - Control laws

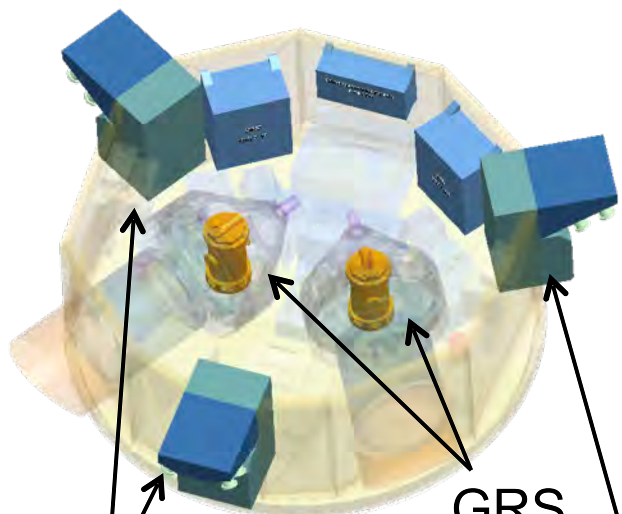


Full Spacecraft Bus

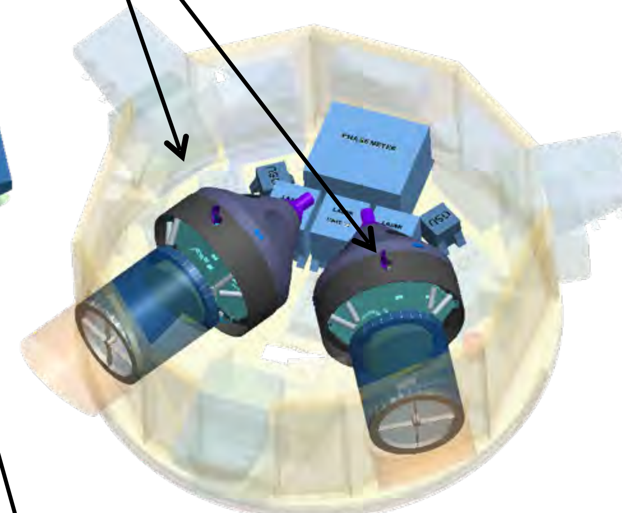


(Note: solar array not shown)

DRS Detail



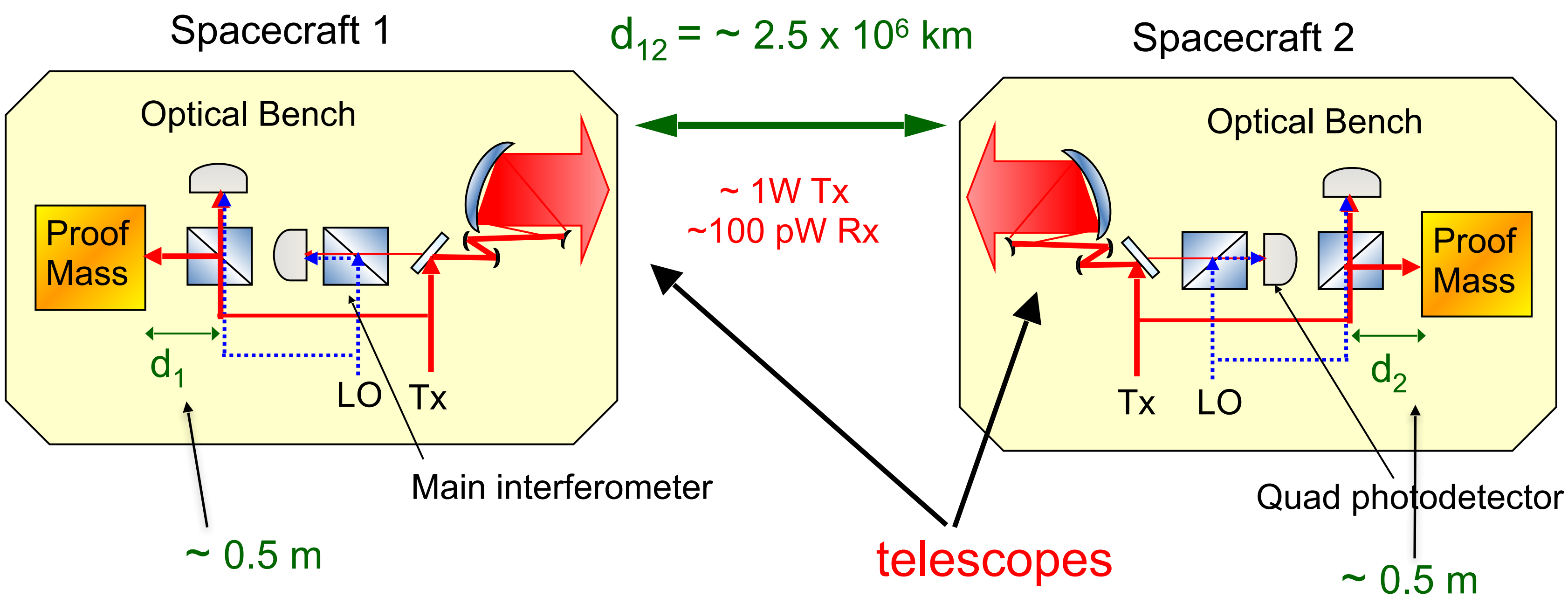
IMS Detail



Inter-Spacecraft Distance Measurement

- **Test-mass to test-mass measured in 3 parts:**
  - 2 × test-mass to spacecraft measurements (short-arm: LPF tests this)
  - 1 × spacecraft to spacecraft interferometer (long-arm)

total separation = $d_1 + d_{12} + d_2$



TELESCOPE DESCRIPTION

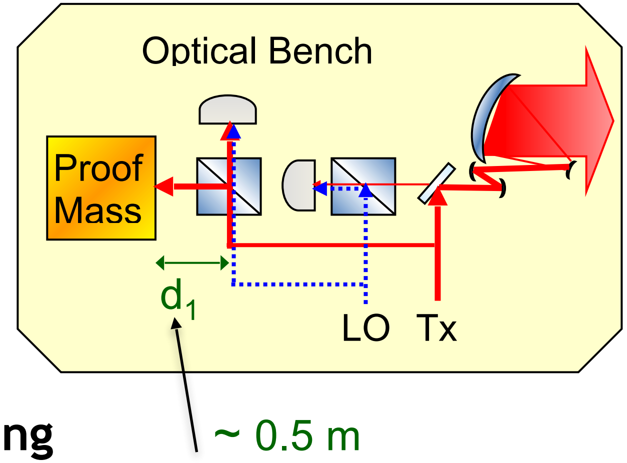
Telescope Functional Description/Requirements

- **Afocal beam expander/reducer**
  - 300 mm dia. primary
  - 2.24 mm dia. on bench
  - 134X magnification
- **Simultaneous transmit and receive**

$$P_{\text{received}} \propto D^4_{\text{primary}}$$

- **Conjugate pupils to minimize tilt to length coupling**
  - Map angular motion of the spacecraft jitter to angular motion on the optical bench without lateral beam walk or piston
- **Smooth wavefront ($\lambda/30$) to minimize tilt to length coupling, also helps maximize on-axis power transmission**
- **Dimensionally stable (path-length fluctuations directly compete with pm scale measurement)**
- **Low back-scatter of transmit beam into receiver**

$$\sim 1\ \text{W transmitted}, \sim 500\ \text{pW received}$$



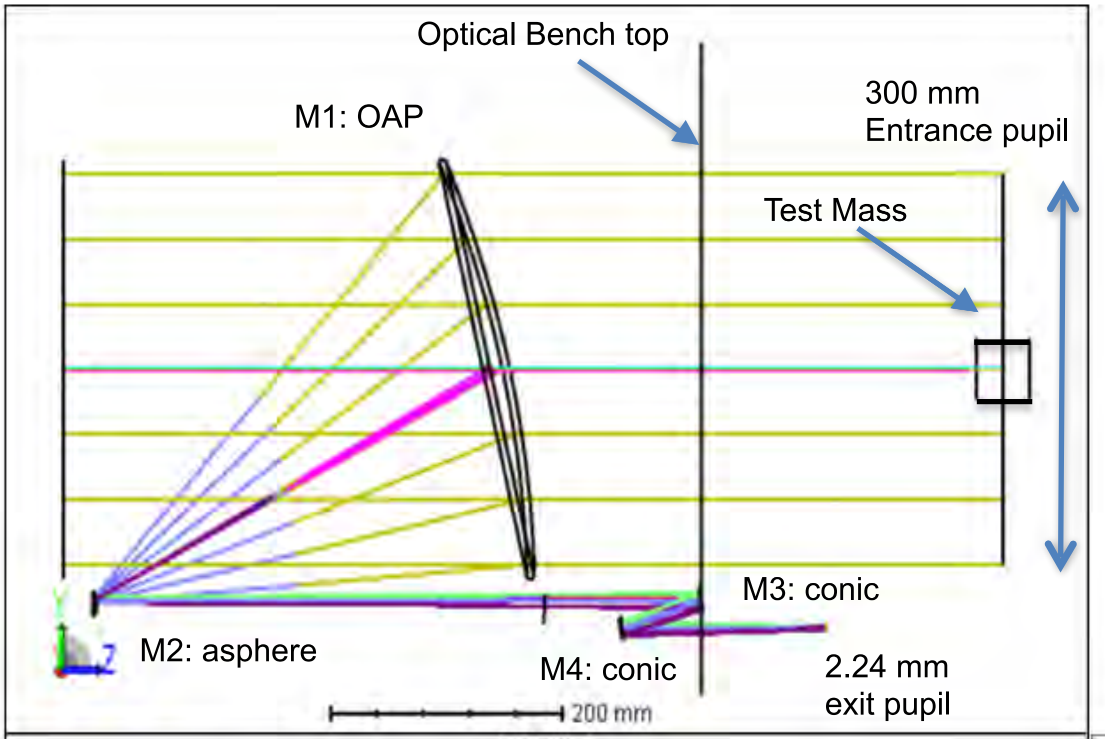
Key Telescope Requirements

Parameter	Driven by	Required Value
Primary diameter	Shot noise (power transmission and collection, $P_{received} \propto D^4_{primary}$)	300 mm
Optical throughput (power efficiency)	Shot noise ($SNR_{shot} \propto 1/\sqrt{P_{received}}$)	$\eta > 0.85$
Entrance pupil (large aperture) diameter	Shot noise	300 mm
Entrance pupil (large aperture) location	Tilt to length coupling	In the plane of the COM of the PM (virtual)
Exit pupil (small aperture) diameter	Optical bench design	2.24 mm
Exit pupil (small aperture) location	Optical bench design	200-250 mm behind primary
Afocal magnification	Optical bench design	$300/2.24 \simeq 134$x
Field of regard (acquisition detector)	Link acquisition	$\pm$ 500 µrad (approx. 0.03° or 100″)
Field of regard (science detector)	Spacecraft orbits	$\pm$ 20 µrad (approx. 4″)
Field of view (science detector)	Stray light	$\pm$ 8 µrad (approx. 1.7″)
Exit pupil (small aperture) distortion	Heterodyne efficiency (SNR)	< 10 %
Optical path length stability	Phase noise in series with main science measurement	$< 1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}\,\sqrt{\left(1+\left(\frac{3\,\mathrm{mHz}}{f}\right)^4\right)}$, for $1 \times 10^{-4} < f < 1$ Hz
Back-scattered light from transmit beam	Phase noise in series with main science measurement	$< 1 \times 10^{-10}$ into Science field of view
Wavefront error	Pointing errors couple wavefront aberration into phase noise in series with the main science measurement	$\lambda/30$ rms in the Science field of regard

challenging

challenging

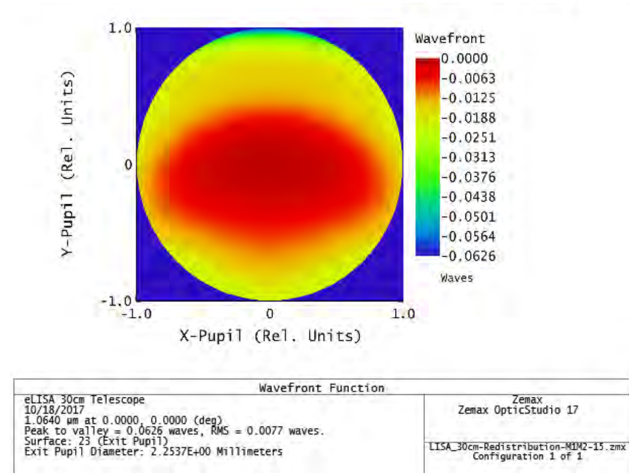
Current 4-mirror Design



M1/M2 Angular Magnification reduced from 74 to 55.8X (25% reduction)
M3/M4 now 2.4X, total is still 134X

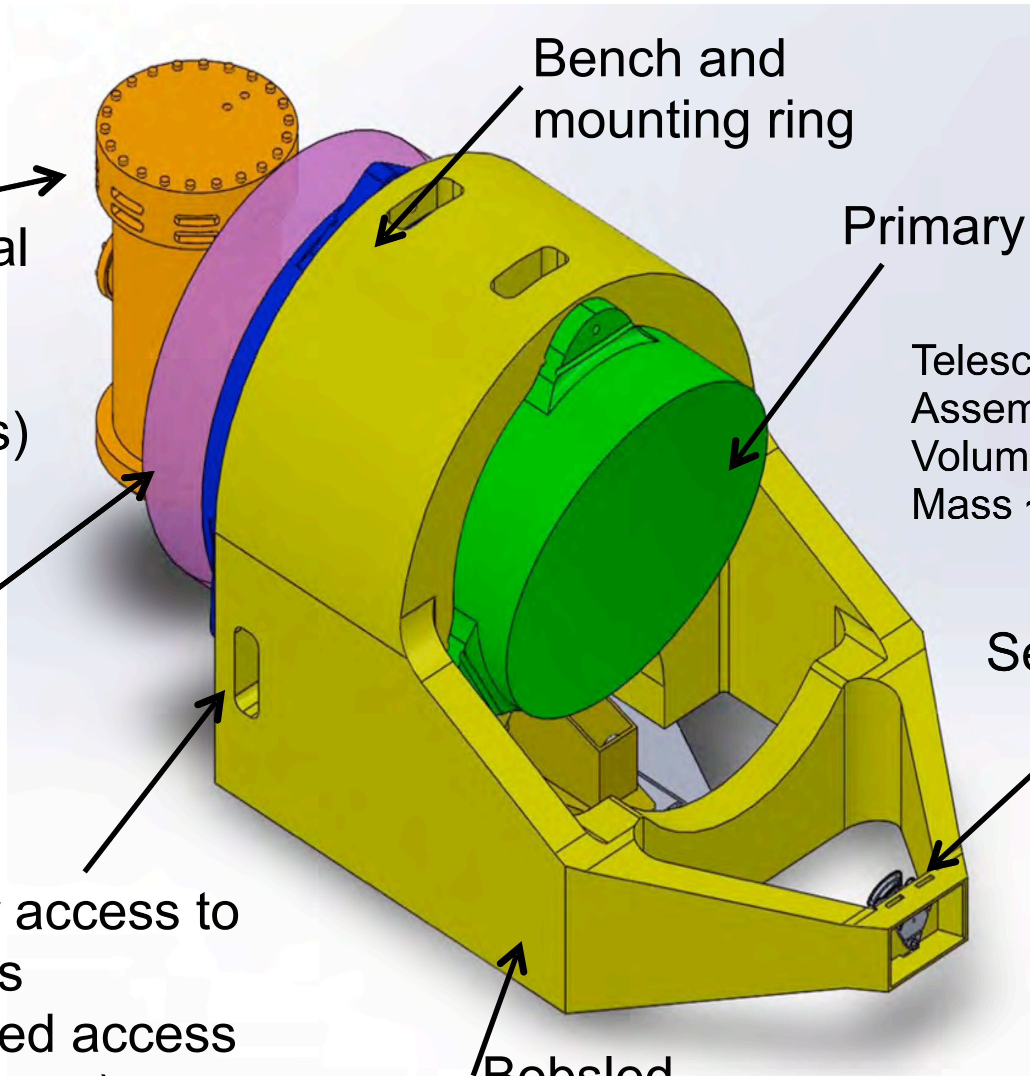
Further M1/M2 Magnification reduction in process

Design residual WFE: 8.2 nm rms



- **Off-axis Cassegrain for stray light performance**
- **Schwarzschild-style pupil extender**
- **Simplified Design to reduce mirror cost, risk**

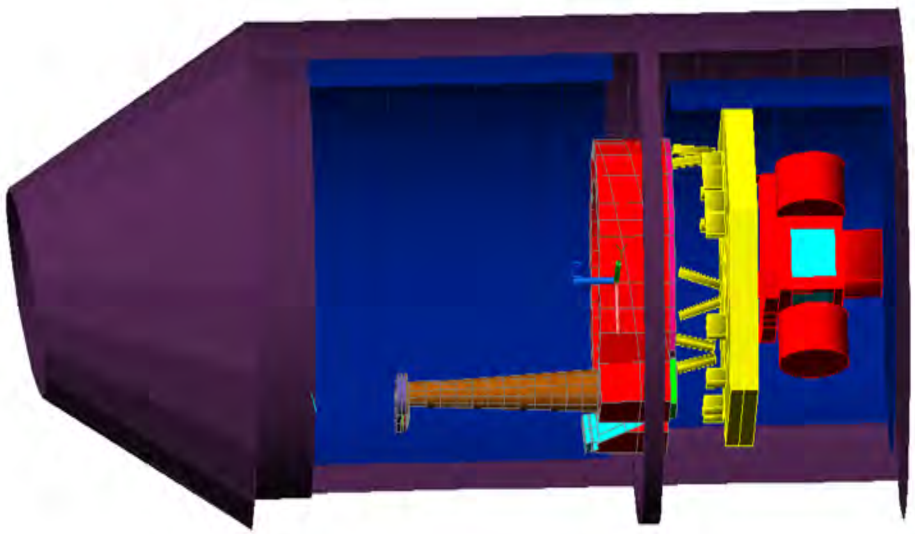
Extended “Bobsled”



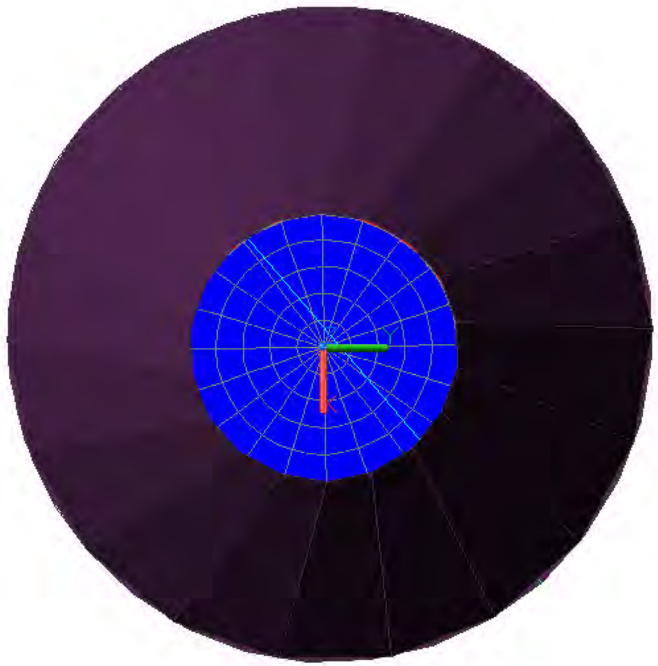
Telescope length ~ 450 mm
Assembly dia ~ 450 mm
Volume ~ 30 liters
Mass ~ 15 kg (just telescope)

Note: this is a concept. Details are not finalized.

Preliminary Thermal Modeling



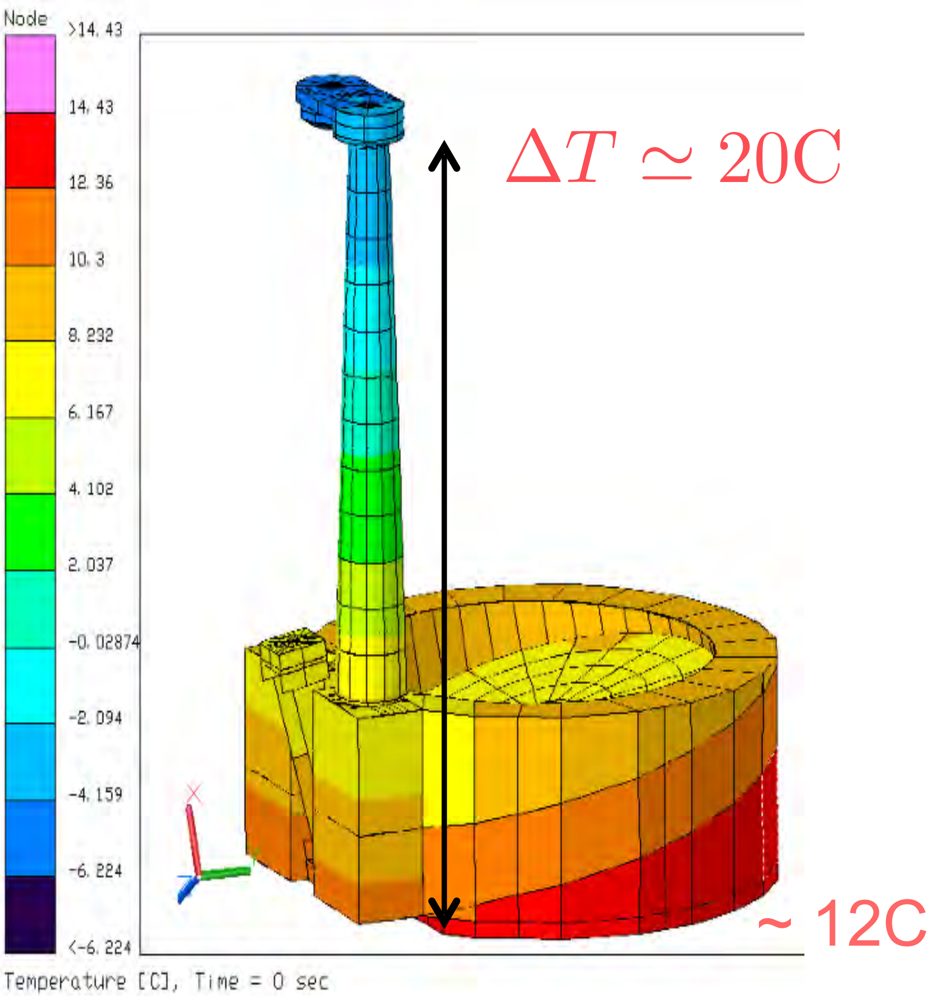
Primary baffled, secondary does not view cold space



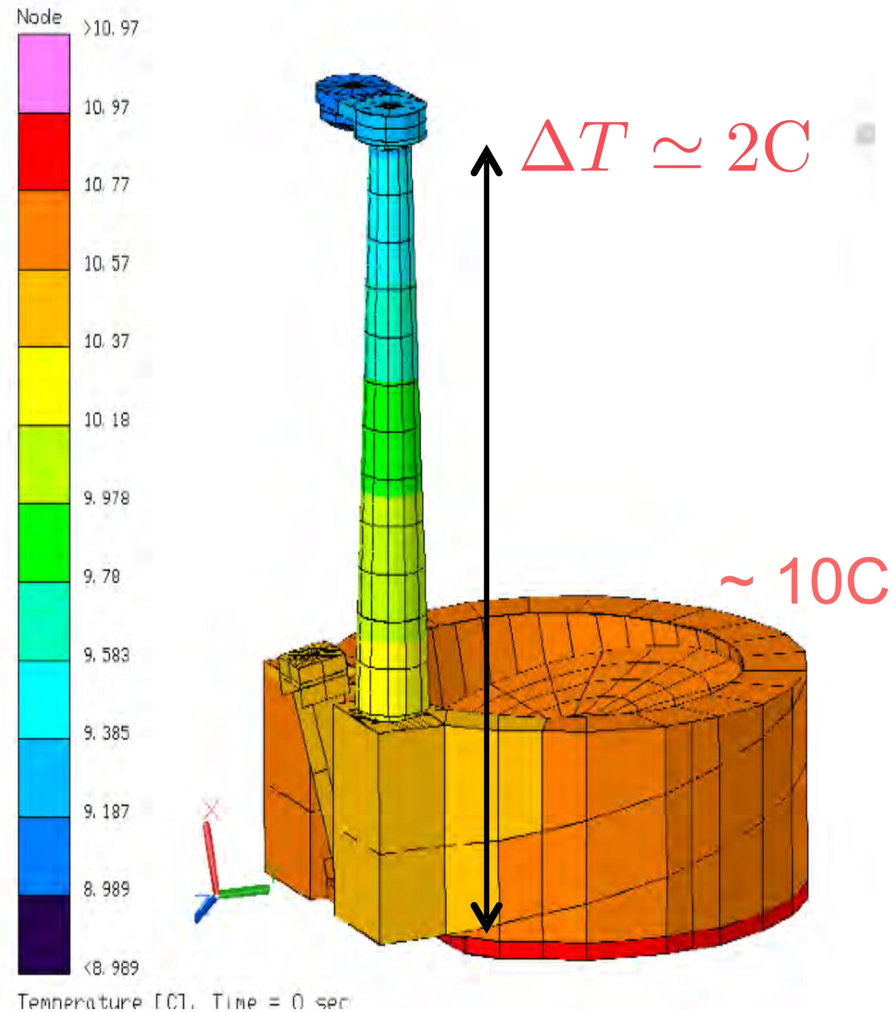
View from space

Materials choice

ZERODUR® like properties



Silicon Carbide like properties



CHALLENGES

SiC Spacer Dimensional Stability Demonstration

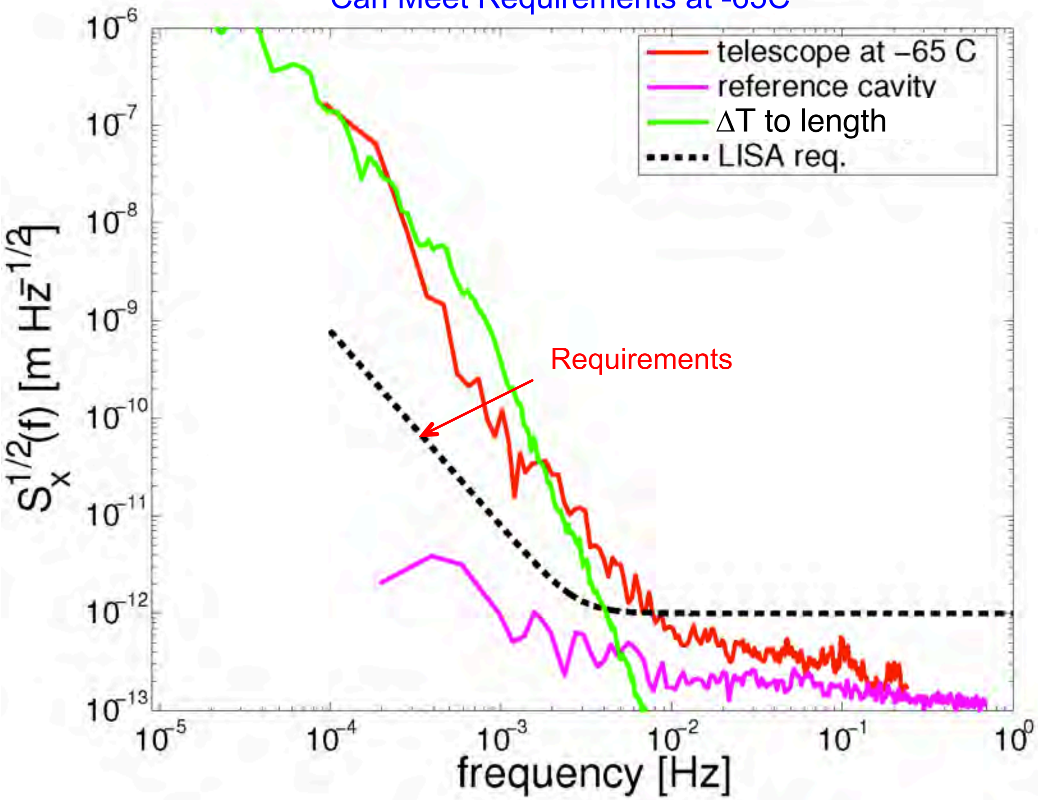
Spacer Activity Objective

- 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 meets stability requirement with on-orbit ΔT(f)
- On-axis Quadpod would not meet scattered light requirement

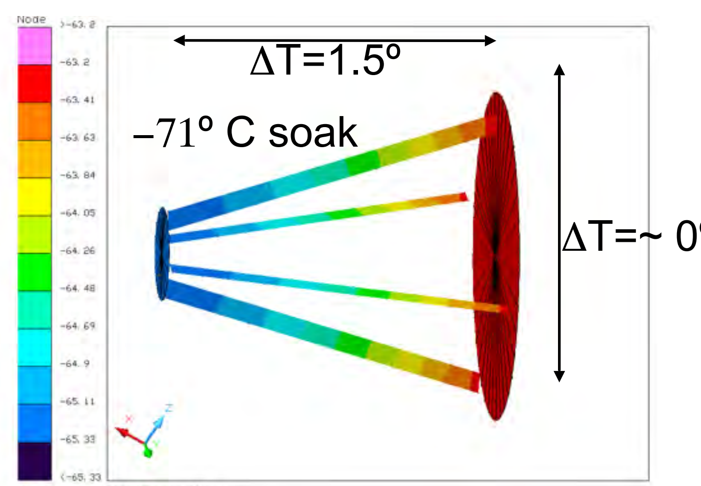
SiC Spacer Design: QuadPod

SiC Spacer Design

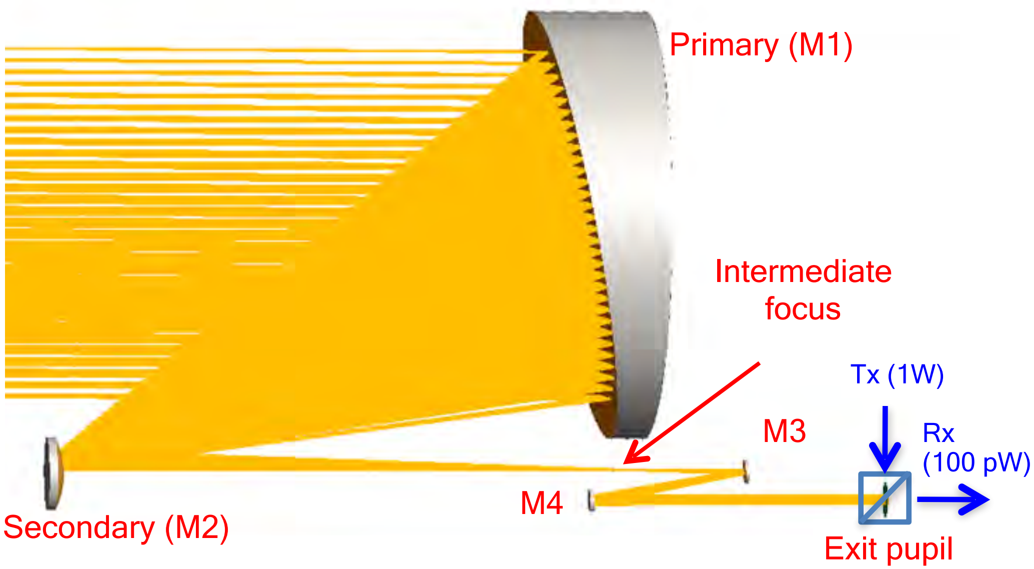
Can Meet Requirements at -65C



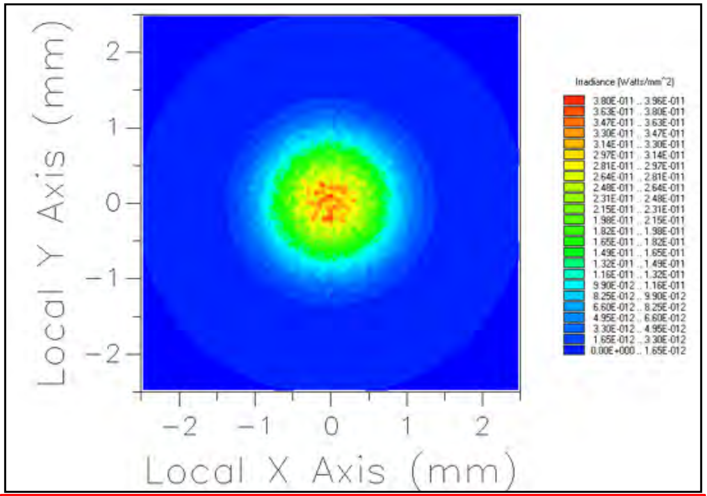
Thermal Model to Determine Test Conditions



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

	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

Summary

- **Gravitational waves enable dramatic new window on the Universe**
- **Precision metrology application drives requirements, not image quality**
  - Pico-meter-level pathlength stability
  - Low coherent backscattered light
  - Minimize tilt-to-length coupling
- **Requirements drive design**
  - Zerodur for pathlength stability
  - Off-axis for scattered light
  - Pupil relay to minimize tilt-to-length
- **Robust, manufacturable design**
  - Approximately 10 units needed