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

Jeff Livas for the US LISA Telescope Team
NASA Goddard Space Flight Center
Greenbelt, MD 20771
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Telescope Team

GSFC Gravitational Astrophysics branch [663]:
  - Jeff LIVAS, Ryan DEROSA, Shannon SANKAR

GSFC Optics branch [551]:
  - Peter BLAKE, Joseph HOWARD, Ritva KESKI-KUHA, Hui LI, Len SEALS, Anita THOMPSON, Garrett WEST

Newton Engineering (mechanical):
  - Justin WARD, Joseph IVANOV, Alex MILLER

EDGE Space Systems (thermal): Angel DAVIS

Genesis Engineering: Mike Miller

University of Florida:
  - Professor Guido MUELLER’s group

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Outline

- Mission Context and Science
- Measurement Principles
- Telescope Description
- Challenges
- Summary
MISSION CONTEXT AND SCIENCE
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 $8.0 \times 10^4$ 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 $2.74_{-0.01}^{+0.04} M_\odot$. The source was localized within a sky region of 28 deg$^2$ (90% probability) and had a luminosity distance of $40_{-14}^{+8}$ Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the $\gamma$-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 $\gamma$-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
Why is this important?

The Gravitational Wave Spectrum

- Quantum fluctuations in early universe
- Binary Supermassive Black Holes in galactic nuclei
- Compact Binaries in our Galaxy & beyond
- Compact objects captured by Supermassive Black Holes
- Rotating NS, Supernovae

Sources

- Richest set of sources
- ESA L3 (2034 launch)

Wave period
- Age of universe
- Years
- Hours
- Seconds
- Milliseconds

Log(frequency)
- -16
- -14
- -12
- -10
- -8
- -6
- -4
- -2
- 0
- +2

Detectors

- Cosmic microwave background polarization
- Pulsar Timing
- Space Interferometers
- Terrestrial interferometers

BICEP-2/WMAP/Planck Detection 2018-20?
Detection 2015!

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
  

- 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”

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

- Measurement concept
  - Measure distance changes between free-falling mirrors
  - Preferred measurement conditions:
    - A long measurement path to make $\Delta L$ 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

DRS Detail

IMS Detail

(Note: solar array not shown)
Inter-Spacecraft Distance Measurement

- Test-mass to test-mass measured in 3 parts:
  - $2 \times$ test-mass to spacecraft measurements (short-arm: LPF tests this)
  - $1 \times$ spacecraft to spacecraft interferometer (long-arm)
  - total separation = $d_1 + d_{12} + d_2$

$d_{12} = \sim 2.5 \times 10^6$ km
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
  \[ P_{\text{received}} \propto D_{\text{primary}}^4 \]
- 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
  \(~ 1 \text{ W transmitted, } ~ 500 \text{ pW received}~\)
# Key Telescope Requirements

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

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

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
Extended “Bobsled”

- Gravitational Reference Sensor (proof mass)
- Primary
  - Telescope length ~ 450 mm
  - Assembly dia ~ 450 mm
  - Volume ~ 30 liters
  - Mass ~ 15 kg (just telescope)
- Secondary
- Rear “keep out” zone
- Slots for access to fasteners (may need access to bench too)
- Bench and mounting ring

Note: this is a concept. Details are not finalized.
Primary baffled, secondary does not view cold space

View from space
Materials choice

**ZERODUR® like properties**

\[ \Delta T \approx 12^\circ C \]

**Silicon Carbide like properties**

\[ \Delta T \approx 20^\circ C \]

\[ \Delta T \approx 2^\circ C \]

\[ \sim 10^\circ C \]
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 $\Delta T(f)$
- On-axis Quadpod would not meet scattered light requirement

SiC Spacer Design

Can Meet Requirements at -65°C

thermal model to determine test conditions

- $\Delta T=1.5^\circ$ to length
- $\Delta T=\sim 0^\circ$

-71°C soak

- $S_{1/2}(f) [\text{m Hz}^{-1/2}]$
- requirements

- frequency [Hz]
- requirements
Scattered Light Analysis

- Source power = 1W
- Total power on the detector = 6.6x10^{-11} W \rightarrow (barely) meets specification of less than 10^{-10}

## Exit pupil

<table>
<thead>
<tr>
<th>Mirror</th>
<th>RMS surface roughness (Å)</th>
<th>MIL-STD 1246D CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>15</td>
<td>300</td>
</tr>
<tr>
<td>M2</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>M3</td>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>M4</td>
<td>5</td>
<td>200</td>
</tr>
</tbody>
</table>

Conflicting accounts of on-orbit levels

- aften 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 coupling
- Robust, manufacturable design
  - Approximately 10 units needed