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
Nov 2017
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

This work was supported by NASA grants 11-SAT11-0027 and 14-SAT14-0014.
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 $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of $28 \text{ deg}^2$ (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 $\gamma$-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

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

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

Wave period
- Age of universe: years
- GW imprint on inflation

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

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

Why is this important?

GW imprint on inflation

Richest set of sources

Detection 2015!

Detection 2018-20?
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 pm/$\sqrt{\text{Hz}}$ / 5 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

(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 = $d_1 + d_{12} + d_2$

\[ d_{12} = \sim 2.5 \times 10^6 \text{ km} \]

![Diagram of Inter-Spacecraft Distance Measurement]

- Spacecraft 1
  - Optical Bench
  - Proof Mass
  - $d_1 \approx 0.5 \text{ m}$
  - Main interferometer

- Spacecraft 2
  - Optical Bench
  - Proof Mass
  - $d_2 \approx 0.5 \text{ m}$
  - Quad photodetector
  - $\sim 1\text{W Tx}$
  - $\sim 100\text{ pW Rx}$
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**

- **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 (λ/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**
  \[ P_{\text{received}} \propto D_{\text{primary}}^4 \]
  \[ \sim 0.5 \text{ m} \]
  \[ \sim 1 \text{ W transmitted}, \sim 500 \text{ pW received} \]
# 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, $P_{\text{received}} \propto D_{\text{primary}}^4$)</td>
<td>300 mm</td>
</tr>
<tr>
<td>Optical throughput (power efficiency)</td>
<td>Shot noise ($SNR_{\text{shot}} \propto 1/\sqrt{P_{\text{received}}}$)</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>$\pm 500 \mu\text{rad}$ (approx. $0.03^\circ$ or $100^\prime$)</td>
</tr>
<tr>
<td>Field of regard (science detector)</td>
<td>Spacecraft orbits</td>
<td>$\pm 20 \mu\text{rad}$ (approx. $4^\prime$)</td>
</tr>
<tr>
<td>Field of view (science detector)</td>
<td>Stray light</td>
<td>$\pm 8 \mu\text{rad}$ (approx. $1.7^\prime$)</td>
</tr>
<tr>
<td>Exit pupil (small aperture) distortion</td>
<td>Heterodyne efficiency (SNR)</td>
<td>$&lt; 10 %$</td>
</tr>
<tr>
<td>Optical path length stability</td>
<td>Phase noise in series with main science measurement</td>
<td>$&lt; 1 \text{ pm} / \sqrt{\text{Hz}} \sqrt{(1 + (3 \text{ mm/s})^4)}$, for $1 \times 10^{-4} &lt; f &lt; 1 \text{ Hz}$</td>
</tr>
<tr>
<td>Back-scattered light from transmit beam</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>Wavefront error</td>
<td>Pointing errors couple wavefront aberration into phase noise in series with the main science measurement</td>
<td>$\lambda/30$ 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”

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

*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

$\Delta T \approx 20^\circ C$

$\Delta T \approx 2^\circ C$

~ 12$^\circ C$

~ 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 -65C

**Thermal Model to Determine Test Conditions**

- $\Delta T=1.5^\circ$  
- $\Delta T=\sim0^\circ$

-71º C soak

- $S_1^{1/2}(f)$ [m Hz$^{-1/2}$] vs frequency [Hz]
Scattered Light Analysis

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

### Mirror RMS surface roughness (Å) and MIL-STD 1246D CL

<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

### Path #, # Rays, Power %, Power, 1st scatter surface

<table>
<thead>
<tr>
<th>Path#</th>
<th># Rays</th>
<th>Power %</th>
<th>Power</th>
<th>1st scatter surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>7</td>
<td>74.947</td>
<td>4.942e-11</td>
<td>.20140417_elisa_baseline.M3.Front</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>23.053</td>
<td>1.520e-11</td>
<td>.20140417_elisa_baseline.M4.Front</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>1.9733</td>
<td>1.200e-12</td>
<td>.20140417_elisa_baseline.M2.Front</td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td>0.026184</td>
<td>1.7266e-14</td>
<td>.20140417_elisa_baseline.M1.Front</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>8967324</strong></td>
<td><strong>100</strong></td>
<td><strong>6.5941e-11</strong></td>
<td></td>
</tr>
</tbody>
</table>

Aft optics contribute 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