Telescope Development for a Space-based Gravitational Wave Observatory

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Prepared by Jeff Livas
Shannon Sankar, Peter Blake, John Crow, Joe Howard, Len Seals,
Ron Shiri, Garrett West
NASA Goddard Space Flight Center

Guido Mueller, Alix Preston, Pep Sanjuan
University of Florida
Project Objective and Approach

• Objective:
  
  To design, fabricate and test a telescope to verify that it meets the requirements for precision interferometric metrology for space-based gravitational-wave observatories.

• Key challenging requirements
  – Optical pathlength stability
  – Scattered light performance
  – Manufacturable design

• Approach
  – Develop a telescope design that
    o Meets eLISA technical requirements
    o Can be manufactured (need multiple (~ 10) copies)
    o TRL-5 by CY2018 (nominally for EM model)
  – Commission a study with a commercial optics/telescope vendor for advice on manufacturability
  – Demonstrate we can implement the design
## Telescope Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Derived From</th>
<th>eLISA/NGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Wavelength</td>
<td></td>
<td>1064 nm</td>
</tr>
<tr>
<td>2 Net Wave front quality departure from a collimated beam of a built</td>
<td>Pointing</td>
<td>≤ λ/30 RMS</td>
</tr>
<tr>
<td>telescope subsystem over Science field of regard under flight-like</td>
<td></td>
<td></td>
</tr>
<tr>
<td>conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Field-of-Regard (Acquisition)</td>
<td>Acquisition</td>
<td>+/- 200 µrad (large aperture)</td>
</tr>
<tr>
<td>4 Field-of-Regard (Science)</td>
<td>Orbits</td>
<td>+/- 8 µrad (large aperture)</td>
</tr>
<tr>
<td>5 Field-of-View (Science)</td>
<td>Stray light</td>
<td>+/- 1 µrad (large aperture)</td>
</tr>
<tr>
<td>6 Science boresight</td>
<td>FOV, pointing</td>
<td></td>
</tr>
<tr>
<td>7 Telescope subsystem optical path length’s stability under flight-like</td>
<td>Path length Noise/ Pointing</td>
<td>≤ 1 pm / -√Hz × (1 + \left(\frac{0.003}{f}\right)^2)</td>
</tr>
<tr>
<td>conditions</td>
<td></td>
<td>where 0.0001 &lt; f &lt; 1 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 pm = 10^{-12} m</td>
</tr>
<tr>
<td>8 Afocal magnification</td>
<td>short arm interferometer</td>
<td>200/5 = 40x (+/-0.4)</td>
</tr>
<tr>
<td>9 Mechanical length</td>
<td></td>
<td>&lt; 350 mm TBR</td>
</tr>
<tr>
<td>10 Optical efficiency (throughput)</td>
<td>Shot noise</td>
<td>&gt;0.85</td>
</tr>
<tr>
<td>11 Scattered Light</td>
<td>Displacement noise</td>
<td>&lt; 10^{-10} of transmitted power into +/- 8 µrad Science FOV</td>
</tr>
<tr>
<td>Interfaces: Received beam (large aperture, or sky-facing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Stop Diameter (D) (large aperture)</td>
<td>Noise/ pointing</td>
<td>200 mm (+/- 2 mm)</td>
</tr>
<tr>
<td>13 Stop location (large aperture)</td>
<td>Pointing</td>
<td>Entrance of beam tube or primary mirror</td>
</tr>
<tr>
<td>Interfaces: Telescope exit pupil (small aperture, or optical bench-facing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Exit pupil location</td>
<td>Pointing</td>
<td>13.5 +/- 2 cm (on axis) behind primary mirror</td>
</tr>
<tr>
<td>15 Exit pupil diameter</td>
<td>optical bench</td>
<td>5 mm (+/- 0.05 mm)</td>
</tr>
<tr>
<td>16 Exit pupil distortion</td>
<td>SNR</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>17 Exit pupil chief ray angle error</td>
<td></td>
<td>+/- 10 µrad</td>
</tr>
</tbody>
</table>

SGO-Mid = 250 mm

From U of Glasgow bench design, courtesy of Ewan Fitzsimons and Harry Ward
**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 limited by lab thermal fluctuations
- Would meet requirements on orbit

**SiC Spacer Design: QuadPod**

**SiC Spacer Thermal Environment**

ΔT=1.5°

ΔT=~ 0°

Commercial Vendor: Designs considered

- Both designs have the same nominal requirements
- Exclusion zone (in red) is for bench optics
Commercial Vendor: Manufacturability

- On- vs off-axis mirrors similar in complexity
- On- vs off-axis system alignment similar in complexity
  - Compensation techniques are similar
- Schedule is 16 months for first copy
  - Driver is material availability for SiC (study contractor makes material!)
  - Once material is cast, then machining is the bottleneck
  - “pipeline” approach is possible and reduces recurring schedule to ~ 10-12 months/copy

**Off-axis mirror difficulty**

**On-axis mirror difficulty**
Overall Stability Budget (@ .1 mHz)

At .1mHz, (worst-case scenario within frequency range), the overall path length stability is divided among the following constituents:

<table>
<thead>
<tr>
<th>Contributor</th>
<th>P-V OPL Change (picometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>7.075</td>
</tr>
<tr>
<td>Creep</td>
<td>5.096</td>
</tr>
<tr>
<td>Focus Drive</td>
<td>0.015</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.19</strong></td>
</tr>
</tbody>
</table>

- Approach that can meet the requirement has been identified
  - Prediction is just within derived specification (12.28 pm).
  - Further optimization and more detailed error budget appropriate for subsequent phase

- Thermal prediction approach assumes electronics box loading and solar loading are in phase (conservative approach)
  - Can further increase stability through using a third baffle (extra mass)

- Belief is that creep is a conservative estimate; could be reduced with geometric design developments and better understanding of the time dependant stability of the Invar material
Scattered Light Analysis

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

M3 and M4 contribute most of the scattered light on the detector.

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<tr>
<th>Mirror</th>
<th>RMS surface roughness (Å)</th>
<th>MIL-STD 1246D CL</th>
</tr>
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<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>
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</tbody>
</table>

Conflicting accounts of on-orbit levels.

- Exit pupil
- Intermediate focus
- Primary (M1)
- Secondary (M2)
- M3
- M4

Conflicting accounts of on-orbit levels.

Pupil Plane Scatter Irradiance

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

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Conflicting accounts of on-orbit levels.
Prototype Telescope Design

M1 Mount
Aluminum structure
Z - along optical path

M2 Mount
M3/M4 Assem
Scattered Light Test Bed

- **Validate scattered light model**
  - Determine surface roughness
    - needed to meet requirements
    - Where particulates become important
  - Components get dirty while making measurements
- **M3/M4 dominate budget**
  - Test M3/M4 separately
    - Faster cycle-time than full telescope
  - Use mirrors with different properties
    - Surface roughness
    - Reflective coatings
    - Surface contamination levels
  - Mirrors need not have telescope prescription for some tests
  - Practice alignment techniques
- **Develop analysis pipeline**
  - BRDF (component level) to predict system level
Optical Test Setup

Optical Layout

• Telescope tested double-pass from the small aperture side
• Currently aligned to better than λ/34
• Stable under normal lab conditions
• Room temperature operation only

Measured WFE performance
λ/34, center field, 632.8 nm
SUMMARY/NEXT STEPS

• Prototype installed and aligned
  • Delivered to GSFC 6/5/15 (originally 3/20/15)
  • Reassembled and realigned by 7/27/15
• Tested double-pass with an interferometer (LUPI)
• Residual wavefront error is $\lambda/34$ ($\lambda/30$ spec) at 632.8 nm
• Alignment is stable under laboratory conditions
• Next steps:
  • verify wavefront error at 1064 nm
  • beam dump for transmitted light needed
    • use carbon nanotubes (R < 0.5%)
  • verify scattered light model
• Concern: mirrors are dirty
  • Vendor packaged poorly for shipping
  • May have to try cleaning M1, M2 (no spares)
  • Have clean spares for M3, M4