Telescope Design for a Space-based Gravitational Wave Mission

Status report for the L3 Study Team

Jeff Livas
NASA Goddard Space Flight Center
23 March 2016
Outline

• **Telescope Description**
  – Functional
  – Location on the sciencecraft
  – High-level requirements

• **Technology Readiness Levels (TRLs)**
  – Rough development timeline

• **Rough description of the work to be done**

• **System dependencies that affect design and development plans**
Telescope Description

• Functional:
  – Afocal optical beam expander
    o Classic LISA: 400 mm/5 mm = 80X
    o eLISA: 200 mm/5 mm = 40X
  – Efficiently deliver power from one S/C to another
    o “diffraction limited” lambda/30 at 1064 nm (~ 35 nm)
    o High optical throughput
  – Smooth wavefront to minimize tilt to length coupling
    o “diffraction limited” – minimize wavefront aberrations
      (astigmatism is the leading term)

• Other requirements
  – Dimensionally stable optical pathlength
    o in series with the main measurement
  – Low scattered light (transmit and received simultaneously)
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 $= d_1 + d_{12} + d_2$

$\text{d}_{12} = \sim 2 \times 10^6 \text{ km}$
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
- Disturbance Reduction System
  - Gravitational Reference Sensor (GRS)
  - µN thrusters
  - Control laws

IMS Detail
- Interferometer Measurement System (IMS)
  - Laser
  - Telescope
  - Optical bench

Optical bench mounted in Telescope Assembly

(Note: solar array not shown)
Key Telescope Interfaces

- Optical
- Mechanical
- Thermal

Optical Bench
Proof Mass

MLI

Transverse Temperature gradient

Space at T= 2.7K

Bench at T=300K

200 mm dia collimated beam

5 mm dia collimated beam

Struts on strongback

Applied axial Temperature gradient
Glasgow NGO optical bench design

NGO OB Concept Layout. University of Glasgow.
Simplified Optical Bench Model

- Essential Tx/Rx optics extracted from Glasgow design

- Main interface (for now) is the telescope pupil

- FRED model developed:
  - ideal relay optics added to reduce beam from 5 mm to 1 mm detector dia
  - defines scattered light simplified model for calculation
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Derived From</th>
<th>eLISA flight telescope (for reference only)</th>
<th>Prototype telescope</th>
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</thead>
<tbody>
<tr>
<td>1 Wavelength</td>
<td>1064 nm</td>
<td>1064 nm</td>
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<tr>
<td>2 Wave front Error [WFE] over field of view [FOV]</td>
<td>Pointing</td>
<td>≤ λ/30 RMS</td>
<td>≤ λ/30 RMS</td>
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<tr>
<td>3 Field-of-Regard</td>
<td>Orbits</td>
<td>+/- 20 µrad (large aperture)</td>
<td>+/- 20 µrad (large aperture)</td>
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<tr>
<td>4 Field-of-View [FOV]</td>
<td>Stray light</td>
<td>+/- 8 µrad (large aperture)</td>
<td>+/- 8 µrad (large aperture)</td>
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<tr>
<td>5 Telescope subsystem OPD stability under flight conditions</td>
<td>Path length Noise/ Pointing</td>
<td>&lt; 1 pm/√Hz RMS x ( \sqrt{1+\left(\frac{f_0}{f}\right)^4} ) where 0.0001 &lt; f &lt; 1 Hz, ( f_0 = 0.003 \text{ Hz} ), 1 pm = 10(^{-12}) m</td>
<td>Maintain RMS WFE (req #2) near room temp (T ~ 20 +/- 3°C)</td>
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<tr>
<td>6 Afocal magnification</td>
<td>short arm interferometer</td>
<td>200/5 = 40x</td>
<td>200/5 = 40x</td>
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<td>7 Optical throughput [transmission]</td>
<td>Shot noise</td>
<td>&gt;0.85 at 1064 nm</td>
<td>&gt;0.85 at 1064 nm</td>
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<td>8 Scattered Light</td>
<td>Displacement noise</td>
<td>&lt; 10(^{-10}) of transmitted power into the receiver FOV</td>
<td>&lt; 10(^{-10}) of transmitted power into the receiver FOV (verify by model)</td>
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<td>9 Stop Diameter (D) (large aperture)</td>
<td>Noise/ pointing</td>
<td>200 mm diameter</td>
<td>200 mm diameter</td>
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<tr>
<td>10 Stop location (large aperture)</td>
<td>Pointing</td>
<td>Entrance of beam tube or primary mirror</td>
<td>Entrance of beam tube or primary mirror</td>
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<tr>
<td>11 Exit pupil location (small aperture)</td>
<td>Pointing</td>
<td>140 mm (on axis) behind primary mirror</td>
<td>140 mm (on axis) behind primary mirror</td>
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<td>12 Exit pupil diameter (small aperture)</td>
<td>optical bench</td>
<td>5 mm</td>
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<tr>
<td>13 Focus adjustment</td>
<td>pointing</td>
<td>maintain WFE from room T (300K) to operating (230K) (Verify by model)</td>
<td>Leave provision for manual adjustment</td>
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<tr>
<td>14 Mechanical envelope</td>
<td>spacecraft volume</td>
<td>≤ 450 mm length x 300 mm diameter (TBC)</td>
<td>≤ 600 mm length x 400 mm diameter or as negotiated</td>
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</table>
General Technology Readiness Levels

- **TRL 1** Basic principles observed and reported
- **TRL 2** Technology concept and/or application formulated
- **TRL 3** Analytical and experimental critical function and/or characteristic proof-of-concept
- **TRL 4** Component and/or breadboard validation in laboratory environment
- **TRL 5** Component and/or breadboard validation in relevant environment
- **TRL 6** System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- **TRL 7** System prototype demonstration in a space environment
- **TRL 8** Actual system completed and “flight qualified” through test and demonstration (ground or space)
- **TRL 9** Actual system “flight proven” through successful mission operations

*telescope now*  
*“environment” includes interfaces, not just Temp, Pressure, etc*  
*ESA’s definition is somewhere between these two*
## Table 4-1: Comparison of ISO TRL scale and ESA old TRL scale

<table>
<thead>
<tr>
<th>TRLs in old ESA scale</th>
<th>TRLs in new ISO scale</th>
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</thead>
<tbody>
<tr>
<td>TRLs 1 to 4</td>
<td>TRLs 1 to 4 are basically unchanged</td>
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<tr>
<td>TRL 5</td>
<td>Same definition as TRL 5 old scale, but allowing reduced scale breadboard verification. Most useful for the development of large pieces (telescopes, structures) and for launcher developments.</td>
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<td>TRL 6</td>
<td>TRL 6 Same as TRL 5 old scale</td>
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<tr>
<td>TRL 7</td>
<td>TRL 7 Qualification level, through validation on ground or in orbit, as needed</td>
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<tr>
<td>TRLs 8-9</td>
<td>TRLs 8-9 are basically unchanged</td>
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From “Guidelines for the use of TRLs in ESA programmes”

Prepared by: ESA TRL Working Group
Reference: ESSB-HB-E-002
Issue: 1
Revision: 0
Date of Issue: 21 August 2013
Status: Approved/Applicable
Document Type: Handbook
Distribution:
Notional L3 Development Schedule
Developed by ESA for the Gravitational Observatory Advisory Team (GOAT)

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## One Possible Development Timeline

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<tr>
<th>Year</th>
<th>ESA Activity</th>
<th>NASA Activity</th>
<th>Telescope Dev</th>
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<tr>
<td>2013</td>
<td>concepts study</td>
<td>US L3 Technology Development</td>
<td>Y1 Y2 Ext Y1 Y2 Ext</td>
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<tr>
<td>2014</td>
<td>CATE review</td>
<td>Mid-decadal Review</td>
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<td>2015</td>
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<td>JWST Launch</td>
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<td>2016</td>
<td>L2 Phase A</td>
<td>Funding Ramp for new Probe class mission start?</td>
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<td>2017</td>
<td>L3 AO</td>
<td>AFTA?</td>
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<td>2018</td>
<td>B1 B2</td>
<td>L2 Implementation phase for 2028 launch</td>
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<td>2019</td>
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<td>EM: def L3 AO</td>
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<td>L3 A EM: Dev</td>
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<td>SFC Adoption ITT/Prime Selection</td>
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<td>L3 Phase B2/C/D (8.5 years): mid-2034 launch</td>
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### Notes:
- **This proposal estimated TRL 4**
- **TRL 5/6 Delivery Date to support the L3 Engineering Model**
TELESCOPE STATUS AND WORK TO BE DONE
Previous Work:
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
- On-axis Quadpod would not meet scattered light requirement

SiC Spacer Design: QuadPod

Thermal Model to Determine Test Conditions

ΔT=1.5°

-71° C soak

ΔT=~ 0°
Previous Work:
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
- On-axis Quadpod would not meet scattered light requirement

SiC Spacer Design
Can Meet Requirements at -65°C

Requirements

ΔT=1.5°
-71° C soak
ΔT=~ 0°

It is on the basis of these results that we decided to concentrate on stray light for the next version of the telescope. Note that this is an on-axis structure and does not include mirror realistic mirror mounts.
**Scatter Suppression Masks**

**Key challenge:**
- Simultaneous transmit and receive telescope operation plus an interferometric detection scheme:
  - combines extreme sensitivity (1 pW)
  - With high dynamic range of coexisting optical powers (~ $10^{10}$)
- On-axis (Narcissus) reflection dominates
- Hole or mask yields on-axis Poisson spot
- Petaled masks suppress on-axis spot
- Grey-scale masks do better
- Currently limited by
  - Fabrication errors/defects
- Aaron Spector/Guido Mueller developed spiral mask shape alternative

Currently performance is not yet adequate to use an on-axis design
Current Design:

- Off-axis Cassegrain for stray light performance
- Schwarzschild-style pupil extender
- Simplified Design to reduce mirror cost, risk
- Simplified construction and alignment
- Meets most requirements
Telescope Test Setup

Prototype Telescope

Double-pass telescope test setup

12.5" flat

600 mm

200 mm

Exit Pupil

M1

M2

M3

M4

Entrance Pupil

LUPI Camera

40 mm focal length

135 mm to the lens

LUPI

135 mm from M1

Beam diameter = 5 mm

Prototype Telescope

Double-pass telescope test setup

Laser safety shield

Retro flat mirror

Telescope

LUPI

12.5" flat
Telescope WFE at 2 wavelengths
Oct 1, 2015 data
(Spec is $\lambda/30$ at 1064 nm or 35 nm)

632.8 nm
- Fringes
- OPD (phase)
  - PV 167.8 nm
  - RMS 30.5 nm

1064 nm
- Fringes
- OPD (phase)
  - PV 96.0 nm
  - RMS 22.5 nm

Meets spec at both wavelengths but OPD maps are different!
Scattered Light Analysis

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

<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>
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<td>200</td>
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<tr>
<td>M4</td>
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Scattered Light Test Setup

- Simplified Scattered Light Setup
  - Polarization optics separates input from output beam
  - Modulated laser allows synchronous detection for better noise rejection
Rough idea of work to be done

• **Validate scattered light model**
  – Surface roughness vs particulate contamination
    o What is achievable on-orbit is not known
  – Realistic baffling and stop/aperture design
• **Demonstrate stability and scattered light simultaneously**
  – Materials choice plus good mirror mount design
  – Not worrying about light-weighting mirrors, etc
• **Develop interface specifications**
  – Interface with optical bench
    o Optical: relay optics to GRS, detectors; scattered light/reflection, point ahead
    o Thermal: bench is at ~ 300K, telescope is ~ 230K if SiC
    o Mechanical: stability, etc
  – Transmit/receive beams
• **System level study**
• **Investigate In-field guiding**
  – scattered light specification may be incompatible
• **Other scattered light suppression approaches?**
  – Petaled masks
  – Modulation or digital interferometry
Orbital Motion Compensation Concepts

<table>
<thead>
<tr>
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<th>Moveable Optical Assembly</th>
<th>In-Field Pointing</th>
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<tbody>
<tr>
<td>Telescope</td>
<td>Narrow (+/- 200 µrad) field of view</td>
<td>Wide (+/- 1 deg) field of view</td>
</tr>
<tr>
<td></td>
<td>Moveable optical assembly +/- 1 deg</td>
<td>Fixed optical assembly; beam moves</td>
</tr>
<tr>
<td></td>
<td>Beam path fixed through telescope</td>
<td>Small scanning mirror (no piston)</td>
</tr>
<tr>
<td>Inter-bench</td>
<td>Back-link fiber</td>
<td>Fixed free-space beam</td>
</tr>
<tr>
<td>Issues</td>
<td>Actuator concept demonstrated</td>
<td>Mechanism; Scattered light</td>
</tr>
</tbody>
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Scattered Light Analysis

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

Conflicting accounts of on-orbit levels

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aft optics contributes most of the scattered light: in-field pointing needs more
SYSTEM DEPENDENCIES
System Dependencies

• **Telescope Aperture and Laser Power trade**
  – Key metric is SNR at the detector \( (D^4 \times P_{Tx} = \text{constant}) \)
  – Lower laser power may reduce risk
  – Space telescope cost scales with area

• **Arm length/Orbits**
  – Telescope area scales with length \( (D^4/L^2 = \text{constant}) \)
  – Point ahead angles depend on \( L \)
    – Definitely need a point ahead actuator at \( 5 \times 10^6 \) km
    – Probably do not at \( 1 \times 10^6 \) km
  – Telescope pointing: moveable optical assembly vs in-field guiding
    – Changes the optical design and/or the field of view specification

• **Science targets**
  – Influence overall noise budget balance
    – high frequency (0.1-1 Hz) performance?
    – low frequency (0.0001-0.001)
    – both

\[ P_{Rx} = P_{Tx} \left( \frac{D_{Tx}^2 D_{Rx}^2}{C \cdot L^2 \lambda^2} \right) \]

\( P_{Rx} \): Simplified expression for the received power\(^1\):
BACKGROUND MATERIAL
Resources
Key Facilities

- University of Florida/Gainesville
  - Dimensional stability measurement
    - Large, instrumented vacuum tank used for spacer stability demonstration
    - Vibration and thermal isolation
    - Frequency stabilized laser
  - Need a lead person (postdoc/grad student)
ESA Telescope Work

LISA Telescope Assembly Optical Stability Characterization for ESA

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ABSTRACT

The LISA Optical Stability Characterization project is part of the LISA CTP activities to achieve the required Technology Readiness Level (TRL) for all of the LISA technologies used. This activity aims demonstration of the Telescope Assembly (TA), with a structure based on CFRP technology, that a CTE of $10^{-7}$/K can be achieved with measures to tune the CTE to this level. In addition the demonstration is required to prove that the structure exhibits highly predictable mechanical distortion characteristics when cooling down to -90°C, during outgassing in space and when going from 1g environment to 0g.

This paper describes the test facilities as well as the first test results. A dedicated test setup is designed and realized to allow monitoring dimensional variations of the TA using three interferometers, while varying the temperature in a thermal vacuum chamber. Critical parameters of the verification setup are the length metrology accuracy in thermal vacuum and the thermal vacuum flexibility and stability. The test programme includes Telescope Assembly CTE measurements and thermal gradient characterization.

Keywords: LISA, NGO, telescope, characterization

- **Off-axis design**
  - Optically more complicated, mechanically less
- **Composite (water outgassing issues)**
  - Supports 18 K temperature gradient
- **Low CTE goal (10^{-7}/K)**
  - But – need to demonstrate optical path length stability
An Experiment to test
In-Field Pointing for eLISA

ICSO 2014, Tenerife, Canary Islands, Spain

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10\textsuperscript{th} October, 2014

More recent results may be available