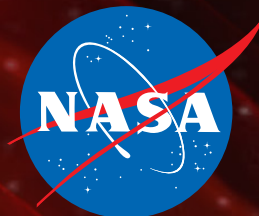


National Aeronautics and Space Administration



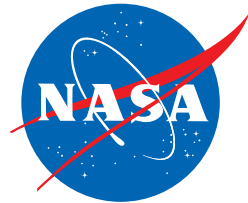
Technology Development Roadmap

A Technology Development Roadmap for a Future
Gravitational-Wave Mission



November 2013

National Aeronautics and Space Administration



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Submitted to

Astrophysics Division
Science Mission Directorate
NASA Headquarters

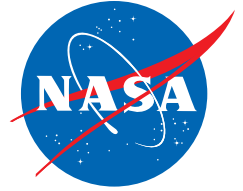
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Technology Development Roadmap for a Future Gravitational-Wave Mission

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Technology Development Roadmap for a Future Gravitational-Wave Mission

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Executive Summary

Humankind will detect the first gravitational wave (GW) signals from the Universe in the current decade using ground-based detectors. But the richest trove of astrophysical information lies at lower frequencies in the spectrum only accessible from space. Signals are expected from merging massive black holes throughout cosmic history, from compact stellar remnants orbiting central galactic engines from thousands of close contact binary systems in the Milky Way, and possibly from exotic sources, some not yet imagined. These signals carry essential information not available from electromagnetic observations, and which can be extracted with extraordinary accuracy.

For 20 years, NASA, the European Space Agency (ESA), and an international research community have put considerable effort into developing concepts and technologies for a GW mission. Both the 2000 and 2010 decadal surveys endorsed the science and mission concept of the Laser Interferometer Space Antenna (LISA). A partnership of the two agencies defined and analyzed the concept for a decade. The agencies partnered on LISA Pathfinder (LPF), and ESA-led technology demonstration mission, now preparing for a 2015 launch. Extensive technology development has been carried out on the ground. Currently, the evolved Laser Interferometer Space Antenna (eLISA) concept, a LISA-like concept with only two measurement arms, is competing for ESA's L2 opportunity. NASA's Astrophysics Division seeks to be a junior partner if eLISA is selected. If eLISA is not selected, then a LISA-like mission will be a strong contender in the 2020 decadal survey.

This Technology Development Roadmap (TDR) builds on the LISA concept development, the LPF technology development, and the U.S. and European ground-based technology development. The eLISA architecture and the architecture of the Mid-sized Space-based Gravitational-wave Observatory (SGO Mid)—a competitive design with three measurement arms from the recent design study for a NASA-led mission after 2020—both use the same technologies. Further, NASA participation in an ESA-led mission would likely augment the eLISA architecture with a third arm to become the SGO Mid architecture. For these reasons, this TDR for a future GW mission applies to both designs and both programmatic paths forward. It is adaptable to the different timelines and roles for an ESA-led or a NASA-led mission, and it is adaptable to available resources.

Based on a mature understanding of the interaction between technology and risk, the authors of this TDR have chosen a set of objectives that are more expansive than is usual. The objectives for this roadmap are: (1) reduce technical and development risks and costs; (2) understand and, where possible, relieve system requirements and consequences; (3) increase technical insight into critical technologies; and (4) validate the design at the subsystem level. The emphasis on these objectives, particularly the latter two, is driven by outstanding programmatic decisions, namely whether a future GW mission is ESA-led or NASA-led, and availability of resources. The relative emphasis is best understood in the context of prioritization.

This TDR identifies four *critical* technologies to be developed at the highest priority: the telescope subsystem, the laser subsystem, the phase measurement subsystem, and the micro-propulsion subsystem. These technologies are all well advanced, and are expected to be possible U.S. contributions to an ESA-led mission, as well as to a NASA-led mission. There are two *key*

technologies: the optical bench subsystem and the Gravitational Reference Sensor (GRS). These are deemed to be a lower priority because there are capable European suppliers. However, there is some European interest in the U.S. supplying the optical bench based on European technology because of production challenges. In the event of a NASA-led mission, the GRS and drag-free control are cornerstone technologies in a GW mission. As such, NASA would benefit from having a deeper understanding of these technologies. There are also beneficial improvements to the European designs. Finally, system testbeds are described here, not because they are critical technology development items, but rather to point out how substantial risk and future cost can be reduced by validating subsystem designs, especially for NASA in the event of a NASA-led mission. While this activity may not fit within available resources, this TDR seeks to identify the opportunity.

As a result of covering a range of designs, two programmatic scenarios, and unknown future resources, there is no simple budget and schedule summary; instead, budget and schedule estimates are provided for each technology, allowing for future flexibility to match development to available resources. This roadmap should be viewed as a temporary plan pending several programmatic decisions. The possibility of an ESA-led GW mission is scheduled to be decided in late 2013; the possibility of a NASA role, if any, in an ESA-led mission will probably be established by 2015. Although the ESA has not released an official schedule other than a nominal launch date in 2028, the successful L2 candidate might initiate pre-Phase A studies in 2016. NASA's actual contributions might not be firmly established until 2016, or later. At the direction of the Astrophysics Division, the schedule in this TDR targets technology readiness level (TRL) 5 by 2018. Developing the four "critical technologies" identified above will require 22.5 full-time equivalents (FTEs) of labor and \$6.3 million in procurement costs.

If ESA does not select a GW mission, then this TDR prepares for a NASA-led mission following the 2020 decadal review. Optimally, that facility-class mission would begin Phase A work about 2021. The TDR schedule targets TRL 5 by 2020. The total investment then depends on the level of support for the "key technologies" and the testbed work. Those decisions are far enough in the budgetary future to be practically unpredictable.

1 Introduction

This document describes a plan for NASA to develop technology for a future gravitational-wave mission. Currently, there is a range of programmatic paths to NASA participation in a gravitational-wave (GW) mission. And there is a range of mission design concepts for a space-based gravitational-wave observatory under consideration. This technology development plan is constructed to support credible programmatic paths and likely mission design concepts. Further, technology development activities are prioritized so that the level of effort can be tailored to the available resources.

This technology development plan has been developed under the auspices of the Physics of the Cosmos (PCOS) [Program Office](#) for the Astrophysics Division at NASA Headquarters. Contributing authors are listed in Appendix A.

The remainder of this introduction consists of: (1) the historical context for the detailed plan that follows in the next chapter, including the origins of the concepts covered by this plan; (2) the technical background on gravitational-wave science, the Laser Interferometry Space Antenna (LISA), and LISA Pathfinder (LPF); (3) the objectives of the technology development plan; (4) an overview of the range of mission design concepts; (5) the investment strategy underlying the plan; and (6) a prioritization of activities and the rationale for it.

1.1 Historical Context

All of the design concepts for future missions derive from the extensive mission formulation work done on LISA over the last two decades. European and U.S. researchers began formulation in 1993 with European Space Agency (ESA) and NASA support. ESA and NASA supported a joint LISA Project from 2000 to 2011. NASA supported directed technology development at the Jet Propulsion Laboratory (JPL) and the Goddard Space Flight Center (GSFC) throughout this period. ESA and its Member States made substantial investments in LISA technologies in this period.

More significantly, both NASA and ESA have participated in LPF, a joint technology demonstration mission. LPF is an ESA-led mission with a European payload, called LISA Technology Package, and a NASA payload, called Space Technology 7-Disturbance Reduction System (ST7-DRS). ST7 was originally a part of NASA's New Millennium Program (NMP) managed at JPL. LPF is currently scheduled for launch in July 2015. LPF is described in Chapter 3.

In Europe, gravitational-wave mission have been proposed for the L1 and L2 calls of ESA's Cosmic Vision Programme. For the initial L1 opportunity in 2011, a consortium of ESA Member States proposed the LISA concept [LISA Yellow Book 2011]. When NASA declined to participate in any of the L1 proposals, the proposers were asked to re-propose descoped concepts. The New Gravitational-wave Observatory (NGO) concept [NGO 2011] was proposed for the second L1 opportunity in 2012. NGO was not selected for that call.

In 2013, ESA issued a call for science themes for the L2 and L3 opportunities of the Cosmic Vision Programme. Responses are in the form of white papers that describe a science case and a notional mission concept for achieving that science. The eLISA Consortium [eLISA Consortium] has proposed the Evolved LISA (eLISA) concept, which is essentially identical to NGO.

During 2011 and 2012, while the European gravitational wave community was developing the NGO concept, the Astrophysics Division of NASA Science Mission Directorate sponsored a Gravitational-Wave Mission Concept Study [GW Mission Concept Study 2012] to examine the interplay of mission architecture on science, risk and cost.

The Gravitational-Wave Mission Concept Study study examined the range of mission concepts addressed by this Technology Development Roadmap. The Space-based Gravitational-wave Observatory High concept (SGO High) [SGO High 2011] was the original LISA design with identical science performance and all known cost savings. The SGO Mid concept [SGO Mid 2011] was a LISA-like concept with all known parametric descopes, but preserving the three measurement arms. The Space-based Gravitational-wave Observatory Low concept (SGO Low) [SGO Low 2011] has the same descopes, but with only two measurement arms. Modulo slight differences in the telescope diameter, it is essentially the NGO/eLISA design. The Mission Concept Study report favored the SGO Mid concept as an attractive compromise between science, cost and risk.

Given the long history of collaboration between NASA and ESA on a gravitational-wave mission and the substantial investments in the LISA mission concept and LISA technology, any gravitational wave mission is likely to be a variant of the LISA design and use technologies already developed for LPF and as part of the ground-based programs. And it is likely to be a partnership between ESA and NASA. For these reasons, this technology development roadmap can encompass the likely range of programmatic outcomes and the likely range of mission concepts.

1.2 Background

This subsection covers three topics to help the reader understand Section 2. Knowledgeable readers can skip this subsection.

The first topic is the science that a space-based gravitational-wave detector is likely to achieve, generally following the science endorsed by the Astro2010 Decadal Survey. The recommendations of the Decadal Survey define the target science for a future gravitational-wave detector.

The LISA mission concept is the second topic. The LISA mission concept is highly developed and extensively analyzed. The requirements that drive technology development are especially well understood. In general, any of the mission concepts being considered for the future will have similar, or slightly relaxed, requirements. As a consequence, many of the requirements are derived from the LISA design, often with no change. Consequently, a summary of the LISA architecture will be helpful in tracing the requirements given in Section 2. LISA documents are frequently be referenced.

LISA Pathfinder is the third topic. Since key technologies have already been developed to a flight-ready status, and will be demonstrated in flight, there is either no need for ground-based technology development, or only a need for supplemental development for those technologies. There are, however, some technologies needed for a gravitational-wave mission not being demonstrated on LPF. Only the concepts of the LISA Technology Package (LTP) and ST7 are described here; a more extensive description can be found in Section 3.

1.2.1 Gravitational-Wave Science

Only very rarely in the history of science has an entirely new spectrum for observing the Universe become accessible. However, this is exactly what will happen this decade, when

gravitational waves will be observed for the first time. Initially, detections will be made using ground-based interferometers at high frequencies (>10 Hz) or with pulsar timing arrays at very low frequencies (<1 μ Hz). However, the full potential of gravitational-wave astronomy will only be realized by high-sensitivity space-based observations in the low frequency band.

The direct observation of gravitational waves in the low-frequency band, 0.1 mHz and 1 Hz, is only possible from space. This band has the most detectable sources, the strongest sources and the richest variety of sources of any known band. Observation of these sources will produce unique insights into the formation of galaxies, the formation and evolution of massive black holes, the end stages of stellar evolution, and the behavior of extreme gravity. Current astrophysics knowledge predicts detectable gravitational radiation from (1) mergers of massive black holes anywhere from the current epoch back to the earliest era of proto-galaxies, (2) the extreme relativistic inspiral of stellar compact objects into the massive black holes at galactic centers, and (3) thousands of compact binaries in the Milky Way. The potential for revolutionary discoveries is unparalleled.

The most comprehensive description of the science that can be done from space is laid out in the LISA science case [LISA Science 2009]. The stated goal of NASA's Astrophysics Division is to carry out as much of the LISA gravitational-wave science endorsed by the Astro2010 decadal as possible. Those endorsements, an abbreviation of the LISA science case, can be found in *New Worlds, New Horizons in Astronomy and Astrophysics* [NWNH 2010] and the report of the *Panel on Particle Astrophysics and Gravitation* [Astro2010 Panels 2011].

The Panel on Particle Astrophysics and Gravitation, the cognizant implementation panel of the 2010 Astrophysics Decadal Survey, summarizes the science from gravitational waves in the form of science questions and the gravitational-wave measurements expected to address those questions, reproduced in Table 1.

Table 1—Science Questions and Gravitational-Wave Measurements
(Adapted from *Astro2010 Panels 2011*, box 8.2, p. 385)

Science Questions	Measurements Addressing the Questions
How do cosmic structures form and evolve?	Tracing galaxy-merger events by detecting and recording the gravitational-wave signatures.
How do black holes grow, radiate, and influence their surroundings?	Using gravitational-wave inspiral waveforms to map the gravitational fields of black holes.
What were the first objects to light up the universe, and when did they do it?	Identifying the first generation of star formation through gravitational waves from core-collapse events.
What are the progenitors of Type Ia supernovae and how do they explode?	Detecting and recording the gravitational wave signatures of massive-star supernovae, of the spindown of binary systems of compact objects, and of the spins of neutron stars.
How do the lives of massive stars end?	
What controls the mass, radius, and spin of compact stellar remnants?	
How did the universe begin?	Detecting and studying very-low-frequency gravitational waves that originated during the inflationary era.
Why is the universe accelerating?	Testing of general relativity—a deviation from general relativity could masquerade as an apparent acceleration—by studying strong-field gravity using gravitational waves in black hole systems, and by conducting space-based experiments that directly test general relativity.

The science case for ESA’s L1 version of LISA is laid out in the ‘LISA Yellow Book’ [LISA Yellow Book 2011]. The science case for the L1 version of NGO can be found in the analogous ‘NGO Yellow Book’ [NGO 2011]. More expansive versions are in the literature [Amaro-Seoane 2012a and b].

1.2.2 The Laser Interferometer Space Antenna (LISA)

From 2001 to 2011, the LISA concept for a space-based gravitational-wave detector was thoroughly studied and developed by joint NASA-ESA science and project teams. A compelling science case [LISA Science 2009] and a robust reference architecture [LISA Concept 2009] were developed, prompting high ratings by the National Research Council (NRC) in the 2000 decadal survey [AANM 2001], the *Connecting Quarks with the Cosmos* review [Q2C 2003], the *Beyond Einstein Program Assessment Committee* review [BEPAC 2007] and the 2010 decadal survey [NWNH 2010].

The technology performance requirements in Chapter 2 are either the same as the LISA requirements, or only slightly modified. The LISA requirements were rigorously flowed down from the LISA Science Requirements Document [LISA ScRD 2007], as described in [LISA Flowdown 2009].

1.2.2.1 Mission Description

The science instrument is a constellation of three ‘sciencecraft’ arranged as an equilateral triangle with 5 Gm arms. Each sciencecraft consists of a tightly integrated scientific payload and a spacecraft bus (Fig. 1). The essential science is the measurement of changes in separation between free-falling test masses in the widely separated spacecraft. This section describes the scientific payload, the spacecraft bus, and the propulsion module.

Scientific Payload

The classic LISA payload is described in [Jennrich 2009]. The scientific payload (Table 2) is divided into a Disturbance Reduction System (DRS) and an Interferometric Measurement System (IMS). The function of the DRS is to place the test masses (TMs) into inertial free-fall along the sensitive axes and within the measurement bandwidth, $0.1 \text{ mHz} < f < 100 \text{ mHz}$. This is accomplished by placing each 4 cm gold-platinum TM in an electrode housing that is used to sense its position and orientation. A set of control laws determines the forces and torques to apply to the two TMs and the spacecraft bus such that TM free-fall, constellation pointing, and Sun angle are maintained. The TMs are actuated via the electrodes while the spacecraft bus is actuated by the Colloidal Micro-Newton Thrusters (CMNTs) and the Optical Assembly Tracking Mechanism (OATM). The LISA design for the Gravitational Reference Sensor (GRS), the TM and supporting subsystems, is essentially identical to that which will fly on ESA’s upcoming LPF mission [McNamara 2013]. The GRS, the spacecraft bus, the CMNTs and the control laws together form the DRS.

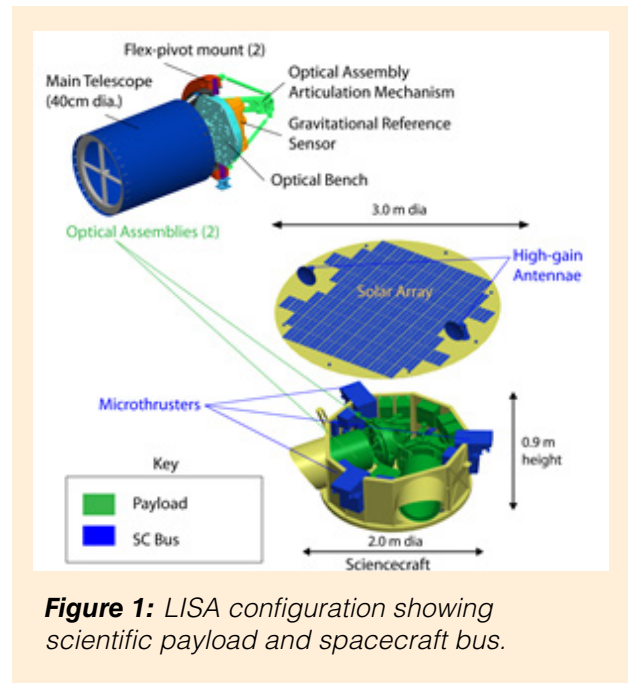


Figure 1: LISA configuration showing scientific payload and spacecraft bus.

Table 2—Major Scientific Payload Components
(TRL levels from Astro2010 RFI#2 [15])

Component	# per S/C	Hardware Description	TRL
Disturbance Reduction System (DRS), Residual TM acceleration requirement: $3.0 \times 10^{-15} \text{ m/s}^2/\text{Hz}^{1/2}$			
Gravitational Reference Sensor (GRS)	2	LPF hardware design, optimized electronics	6
Attitude Control Laws	N/A	18-DOF, each TM drag-free in sensitive direction, S/C attitude adjusted for constellation pointing & Sun angle	6
Colloidal Micro-Newton Thrusters (CMNT)	3 clusters of 4	ST-7/LPF thrusters, 30 μN max thrust, <0.1 $\mu\text{N}/\text{Hz}^{1/2}$ noise (open loop)	6
Optical Assembly Tracking Mechanism (OATM)	2	OA mounted on flex pivot through GRS axis. Piezo inchworm angle actuator. $\sim 1^\circ$ dynamic range, $\sim 8 \text{ nrad}/\text{Hz}^{1/2}$ angular jitter (closed loop)	6
Charge management	2	Ultraviolet (UV) lamps [14]	6
Interferometric Measurement System (IMS), Displacement Sensitivity requirement: $18 \times 10^{-12} \text{ m}/\text{Hz}^{1/2}$			
Laser subsystem	2 + 2 spare	Master oscillator power amplifier (MOPA) design at 1064 nm. Master: 40 mW Nd:YAG NPRO with fiber-coupled phase modulator. Amplifier: 1.2 W Yb-doped fiber amp.	6
Optical Bench	2	Fused silica components hydroxide bonded to Zerodur bench	6
Telescope	2	40 cm, f/1.5 on-axis Cassegrain.	6
Photoreceivers	6 per bench	InGAs quadrant photodetectors with transimpedance amplifiers. 35 MHz BW and 1.8 pA/Hz ^{1/2} noise	3
Phase Measurement System	1	Digital heterodyne receiver based on GPS technology. ~ 60 channels per SC with $\sim 1 \mu\text{cycle}/\text{Hz}^{1/2}$ noise	5
Laser Frequency Stabilization	2	Heterodyne Mach-Zehnder (LPF) or Fabry-Perot cavity. 300 Hz/Hz ^{1/2} residual noise in MBW	5
Point-Ahead Angle Mechanism	2	Piezo-actuated flex pivot mirror on optical bench. Angular range: 800 μrad , angular jitter: 16 nrad/Hz ^{1/2} , piston jitter: 2pm/Hz ^{1/2} (open loop representative specs)	4

The IMS monitors changes in the separation between pairs of TMs on separate spacecraft busses using continuous-wave (CW) heterodyne interferometry. Each GRS is mated with an ultra-stable optical bench and a telescope to form an optical assembly (Fig. 1). Light from a frequency- or phase-stabilized laser is fed to the optical bench and used to make heterodyne measurements. The telescope is used to both transmit and receive light signals along the 5 Gm constellation arms. An optical fiber is used to exchange light between the two optical benches aboard each spacecraft bus. A digital phase measurement system (PMS) measures the phase of the heterodyne signals relative to the local spacecraft clock. Phase measurements from all three spacecraft are combined on the ground to form gravitational wave strain measurements using Time Delay Interferometry (TDI) algorithms [Armstrong 1999].

Spacecraft Bus

The spacecraft bus is designed to meet the requirements of the payload: in particular low levels of mechanical and thermal disturbances in the mHz range. The bus design is described in [LISA Spacecraft 2009] with a few minor changes.

Thermally stability of better than $10^{-6}\text{K/Hz}^{1/2}$ for the payload is achieved with passive thermal isolation. In addition to housing the payload, the bus structure also contains 2 HGAs and 2 omnidirectional antennas for the Communications Subsystem, 12 Coarse Sun Sensors (CSSs) and 2 Star Tracker systems for the Attitude Control Subsystem (ACS). All bus hardware is at TRL 6 or higher.

1.2.2.2 Mission Design

The final operational orbits and trajectories for accessing them are described in this section. The LISA orbit and trajectory analysis is described in [LISA Mission Design 2005].

Orbits

During normal mission science, the constellation forms an equilateral triangle with arms of length $L = \sim 5$ Gm. The center of the triangle follows a circular orbit about the Sun, with radius of 1 A.U. It is located 22° behind the mean Earth; i.e., ~ 58 Gm away. The normal to the triangle plane is tilted away from the Sun by 30° . The triangle rotates about its center at 1 revolution per year.

Perturbations due to Earth's gravity cause constellation breathing that grows over time, eventually distorting the constellation beyond usability. Satellite positions and velocities at just before science initialization must be set so as to minimize constellation distortion over the selected 5-year mission lifetime. Optimization for a typical LISA mission example shows $(\Delta L/L, \Delta v, \Delta/\theta) = \sim(\pm 1\%, \pm 13 \text{ m/s}, \pm 0.8^\circ)$, where $v = dL/dt$, and θ is the angle between two satellites as seen from the third.

Due to constellation rotation and the finite speed of light, each outgoing laser beam must be aimed ahead relative to the corresponding incoming beam by $[\Omega 2L/c] \approx 7 \mu\text{radians}$, where Ω is the rotation rate of the constellation and c is the speed of light.

High Gain Antenna (HGA) range is determined by the rotation of the constellation and the rise and fall of the Earth relative to the plane of the constellation due to eccentricity of the Earth's orbit. The azimuthal range is 360° ; the elevation range is $[8.8^\circ, 13.7^\circ]$.

Trajectories

Detailed, optimized trajectories from post-launch/escape to start of science have been determined for a number of hypothetical launch dates. The bottom line is that the launch vehicle deploys the constellation with a post-escape C3 of $\sim 0.3 \text{ (km/s)}^2$, the trajectory flight to the science orbit requires ~ 13 months, and the total post-release delta-V for each satellite is ~ 1000 to 1100 m/s (distributed in three or four burns during the flight). A propulsion module [LISA Propulsion Module 2009] that is separated from the sciencecraft at the operational orbit provides the required delta-V.

Heuristically, one can imagine the delta-V broken into three logical components: (a) an in-plane breaking burn at perihelion (~ 430 to 490 m/s , depending on launch date); (b) an out-of-plane, inclination changing burn at what will thereafter be a node crossing ($\sim 630 \text{ m/s}$); and (c) a pair of burns at what will be perihelion and aphelion to adjust the eccentricity ($\sim 150 \text{ m/s}$). A straight sum of these parts yields ~ 1210 to 1270 m/s . Optimized construction reduces those results by ~ 15 to 20% .

1.2.2.3 Operations

The ground segment includes the Deep Space Network (DSN), the Mission Operations Center (MOC) at JPL, the Science Operations and Data Processing Centers (SODPC), and a distributed team of science investigators.

The three DSN 34-m X-band antennae communicate with each of the spacecraft directly via a gimbaled HGA. The MOC performs command sequencing, health and safety monitoring, navigation and anomaly investigation. A schedule for DSN passes, HGA positioning, and laser frequency changes is generated for each spacecraft and transferred to the DSN for uplink. Passes are nominally scheduled every other day. Other aspects of operations are autonomous, and consist largely of continuously running control loops and self-recovery from detected faults.

The MOC sends the science data and required engineering data to the SODPC where the instrument performance and data quality are assessed. The SODPC will generate the TDI observables and use this data stream to identify and characterize strong signals. These sources can then be subtracted from the TDI data stream to reveal underlying weaker signals. The resulting data output will be a catalog of sources with estimated parameters that is periodically updated as additional data is processed. The science centers will also provide a higher level of quality assurance for overall instrument performance and may periodically request engineering tests or configuration changes of the constellation or one spacecraft. These requests will be negotiated with the MOC for assessment and disposition.

The distributed team of investigators accesses the data through public networks, and performs focused investigations of specific sources and phenomena. Results are returned to the SODPC for archival and use in further data reduction.

The mission can be divided into the following phases: launch and cruise (14 months total), commissioning (4 months), science operations (60 months), and de-commissioning.

The four spacecraft/prop module pairs will share a single launch into Earth-escape orbit and will each cruise to their respective positions in the constellation. During this cruise phase,

some initial check out of the spacecraft will be performed, although a number of systems (e.g., CMNTs, GRS, long-arm interferometry) cannot be fully activated until after the spacecraft has separated from the propulsion module. At the end of the cruise phase, the propulsion modules will be ejected, leaving the spacecraft with CMNTs for attitude control and drag-free operations. The test masses will be placed into drag-free flight and the six 5 Gm links will be established. During science operations, the constellation will be stable by virtue of initial conditions without any maintenance maneuvers. Science operations will last 2 years. An extended mission will be limited by constellation degradation (e.g., increased inter-spacecraft Doppler shifts and larger angular variations) as well as reduced communication bandwidth.

The communications data volume and operations will be consistent during science operations, with the constellation generating 1.3 Gbit/day, and requiring each sciencecraft to have an 8-hour DSN contact every 6 days. Key operations are re-pointing high gain antennas and switching laser frequencies, both of which interrupt science operations and which will be coordinated to minimize outage times.

1.2.2.4 Launch Vehicle

The launch vehicle must accommodate the mass and size of the three sciencecraft, three propulsion modules and the launch vehicle adapter.

The wet mass of each sciencecraft and propulsion module pair is 1726 kg. The estimated mass of the launch vehicle adapter is 284 kg. The total launch mass for three sciencecraft, three propulsion modules, and the launch adapter is 5462 kg.

Several medium-class launch vehicles are capable of launching LISA into its escape trajectory with $C3 = 0.3 \text{ (km/sec)}^2$.

The Atlas V (541) and the Falcon Heavy are illustrative examples. The Atlas V (541) has a launch margin of 103 kg. The Falcon Heavy has a launch margin of 8,071 kg, far more than the total launch mass. The Falcon Heavy is cheaper and is capable of launching two such payloads and still have a launch margin of 2,609 kg. Therefore, the baseline is a shared Falcon Heavy launch to further reduce costs. A shared launch introduces additional constraints and risk, which could have a cost impact.

The launch stack can easily be accommodated in either the Atlas 4 m fairing, or in the Space-X 5-m fairing.

1.2.3 LISA Pathfinder

LISA Pathfinder (LPF) is an ESA-led LISA technology demonstration mission [McNamara 2013], scheduled to launch in July 2015. It carries an ESA payload, called the LTP, and a NASA payload, called ST7-DRS, which is a flight project initiated under the New Millennium Program at JPL. Since sufficiently low-noise levitation of a test mass in six degrees of freedom is unobtainable in a terrestrial laboratory, the principal goals of both payloads are to demonstrate drag-free flight at a level approaching that required by LISA and to validate disturbance noise models. LPF is described in more detail in Section 3.

The LTP consists of two GRSs, an interferometer measurement system measuring the separation of the test mass with respect to each and with respect to the spacecraft surroundings. The

Drag-Free Attitude Control System holds the spacecraft fixed with respect to one of the test masses through cold microthrusters. The second GRS is used as a witness reference to measure the residual acceleration noise on the test masses. The ST7 package uses the LTP GRSs, but its own control system and colloid microthrusters.

The GRSs are designed to fulfill LISA's disturbance requirements. Copies of the LTP designs could be used on a future GW mission. The interferometry is similar—but not identical—to the short-arm interferometer in the LISA IMS. The colloid microthrusters are also designed to LISA requirements, but will need a large propellant supply and longer lifetime for a future GW mission.

LPF is now in late Phase D, with launch scheduled in 2015. The flight units of the U.S. technology have been qualified and integrated onto the LPF spacecraft for nearly 2 years. The European technologies have been qualified, and flight units for all but the test mass launch lock, the electrode housing and the microthrusters are ready for final integration. Because a previous thruster technology was deemed not ready, the LPF spacecraft is being retrofitted for cold gas thrusters that have already been developed for the Gaia mission.

The knowledge of the LISA design and technology and the existence of flight units strongly favors mission concepts that take advantage of these very substantial investments. An extraordinary amount of development risk has been retired.

1.3 Objectives

The usual objective of a technology development roadmap is to reduce technical and programmatic risk by bringing the technologies associated with a specific mission design concept to a level of technical readiness by some date associated with a project timeline. A common milestone is TRL 6 by Preliminary Design Review (PDR).

In the case of a future gravitational-wave mission, there is some variation between the design concepts under consideration, a project timeline has not been established, and the strategic path forward is uncertain. Fortunately, it is possible to construct a technology development roadmap that encompasses all practical mission design concepts and likely programmatic choices.

This roadmap has the following objectives:

- Risk/Cost reduction—Reduce technical and development risks to ensure that flight hardware that meets the mission requirements can be produced on acceptable budget and schedule.
- Requirement relief—Relieve/understand system requirements/consequences (power consumption, thermal constraints, performance, cost).
- Technical insight for the U.S. community—Develop insight in the critical technologies for a future gravitational-wave mission, especially if it is to be NASA-led.
- Validate design at the subsystem level—Retire risk of design flaws prior to mission formulation/implementation.

1.4 Programmatic Considerations

This section provides a summary of the programmatic considerations included in developing the development roadmap.

This technology development roadmap is constructed to accommodate the range of programmatic paths, address a suite of technology development goals, and adapt to available funds.

The Astrophysics Division at NASA Headquarters and the PCOS Program Office are considering two strategic paths forward to implement a gravitational-wave mission. *New Worlds, New Horizons in Astronomy and Astrophysics* [NWNH 2010], the National Research Council's decadal survey of astronomy and astrophysics for the decade 2010-2020, prioritized a gravitational-wave mission as the second highest priority facility class project. However, budgetary constraints prohibit the implementation of such a mission in this decade.

The two paths forward are: a partner with the European Space Agency L2 opportunity of their Cosmic Vision Programme, or a NASA-led mission commencing in the 2020-2030 decade. The first option promises an earlier start and a launch around 2028, but is contingent on ESA selecting a gravitational-wave mission for L2 and a successful LPF mission. The second option assumes a Phase A mission start no earlier than 2020.

The purpose of this document is to lay out the technology development to support either of these options.

1.4.1 Technology Development Considerations

A range of technologies is required for a gravitational wave mission. Several of these are being demonstrated on the LPF, scheduled to launch in 2015. Options for several technologies exist, and these may be developed within the U.S. or among foreign partners. Launch dates are uncertain, and could vary between 2028 and the mid-2030s.

Two options for a gravitational wave mission concept are considered here:

- a) An ESA-led mission with NASA as a junior partner, selected as part of the present L2 mission call. This mission would nominally be started in 2015 with a launch date in 2028.
- b) A NASA-led facility class mission. This mission would be started in 2020 with a launch date after 2030.

In developing the plan, the technologies to be developed were assumed to have to be at TRL 5 by 2018 to support an ESA-led mission. Technologies for supporting a NASA-led mission were assumed to be required to be at TRL 5 by 2020.

The plan was developed to maximize the ability to support either approach. Technologies were prioritized between those most likely to be contributed to an ESA-led L2 mission, and those which would only be required for a NASA-led mission. Any technologies developed for an ESA-led mission would also apply to a NASA-led mission. Accordingly, the development schedule was set to allow for developing the technologies applicable to an ESA-led mission to TRL 5 by 2018. Technologies which were only required for a NASA-led mission could begin development later.

Each technology can be developed independently of the others. The tasks, durations, and resource requirements for each technology were individually identified. The phasing of the technology development efforts may therefore be adjusted, if required, due to fiscal year resource limitations. It is also recognized that the exact technologies to be contributed to an ESA-led mission would be

subject to NASA-ESA negotiations, and the development sequence may therefore subsequently be varied to support the results of these negotiations.

1.5 Prioritization

To adapt this technology development roadmap to the programmatic options described in the previous section, the included technologies are prioritized into three categories. These categories are chosen to adapt to the timelines and roles for NASA. The technologies needed in the nearer term for an ESA-led mission are deemed 'critical,' and those needed at a later date for a NASA-led mission are characterized as 'key.' A third category for system testbeds is included because of the potential for long-term risk reduction and cost savings. There is no prioritization within categories.

1.5.1 Critical Technologies

The highest priority technologies in this roadmap are: (1) the telescope subsystem, (2) the laser subsystem, (3) the phase measurement subsystem, and (4) the micro-propulsion subsystem. The rationale for these "critical technologies" as the highest priority follows.

The most immediate need for technology development is content that NASA can supply to an ESA-led L2 mission. However, those technologies will be negotiated 2 or more years in the future. In that negotiation, NASA will have to offer flight content that (1) has clean, manageable interfaces in the mission architecture; (2) is at a suitable readiness level; (3) fits within NASA's budget; and (4) ESA wants.

There are several considerations that can be expected to influence what ESA wants. As a risk containment strategy, ESA has asserted that any contribution from a non-European source, like NASA, be replaceable from a European source.

In the usual organization of ESA missions, ESA supplies the spacecraft, final integration and test, the launch, mission operations, mission systems engineering and project management, and the Member States deliver the subsystems of the payload and provide science analysis. Keeping within the ESA-mandated 20% limit on contributions, NASA could contribute payload or spacecraft content. NASA's budget may be more restrictive.

ESA will supply the telescope subsystem and the laser subsystem for eLISA, content that might normally be considered part of the payload. The micro-propulsion subsystem and the drag-free control system, excluding the GRS, are traditionally considered spacecraft subsystems within ESA. At present, there is no established source of telescopes in Europe, although there are credible vendors NASA could supply the laser and micro-propulsion subsystems in place of lasers from a German supplier, or the cold gas propulsion subsystem employed on LPF. These subsystems have relatively simple interfaces, whereas the drag-free control system does not. A NASA contribution of the telescope, laser, and/or micro-propulsion subsystems would relieve ESA costs.

The Member States in the eLISA Consortium have agreed to a preliminary allocation of payload content. A NASA contribution must be compatible with the final European allocation of payload content. At present, there is not a European source for the phase measurement subsystem. Germany has been working on a laboratory prototype, and recently partnered with the Danish Technical University, which has a long history of producing flight hardware, notably star trackers. The U.S. is more advanced technically and has far more experience in relevant flight hardware.

The optical bench subsystem is not included in the “critical technologies” at this time. The University of Glasgow has developed this technology for LPF and delivered a flight model that meets or exceeds LISA performance requirements, although it does not have the full complexity needed by LISA-like missions. However, the greater complexity (90, rather than 30, optical components) and greater number (6, rather than 1) raise production concerns for a university. There may be a compelling argument for a U.S. aerospace contractor to develop faster production methods and a process more tolerant of fabrication errors. Until an interest in U.S. involvement is expressed, the optical bench subsystem is categorized as only a “key technology” for reasons given in the next subsection.

Note again that this selection of critical technologies is based on the best expectations of what will be effective in a future negotiation between NASA and ESA. It is subject to many factors in both Europe and the U.S., and may need revision at a later time.

1.5.2 Key Technologies

The next priority technologies are: (1) the optical bench subsystem, and (2) the GRS. The rationale for these “key technologies” follows.

The optical bench subsystem is the most central subsystem in the payload, interfacing with the laser, phasemeter, telescope, and GRS subsystems. As described previously, there is a strong technology base in Europe, derived from the LPF experience. In an ESA-led mission, this would seem to be a technology best supplied by a Member State of the eLISA Consortium. However, as also mentioned in the previous subsection, there may be reason for the U.S. to collaborate on production aspects of the optical benches. If the Consortium requests a U.S. role, then NASA would have to decide whether to elevate the prioritization of this technology.

In a NASA-led mission, a U.S. capability to produce the optical bench would be extremely valuable, considering its centrality in the payload architecture. This would be most readily accomplished through collaboration with the University of Glasgow, where the expertise now resides.

The Europeans have brought the GRS technology to flight readiness for LPF. The U.S. could make improvements, like the source of UV light for discharging to the design, but ESA is unlikely to ask NASA to supply the entire subsystem.

Even in the event of a NASA-led mission, European Member States are likely to participate as a junior partner and supply the GRS. However, there is considerable value in the U.S. developing deeper insight into this crucial GW technology. The GRS design strongly drives the Disturbance Reduction error budget and functions as the prime sensor for spacecraft attitude and stationkeeping control.

Participation in the LPF mission, especially the testing of the European payload, will be invaluable for understanding the design, operation, and testing of the GRS and the associated Drag-Free Control System. Very small investments by NASA in this activity are leveraged by the very large investments by ESA.

1.5.3 Testbeds

System testbeds are not a critical technology in the usual sense, nor are they requirement to implement a design. However, they are the tool for validating the system design and testing the interactions between subsystems. The LFP experience has shown the value of hardware-in-the-loop tests of system elements. If available early enough in the design process, system testbeds facilitate the discovery of design flaws and the evaluation of design improvements. They also add immeasurably to the understanding of the overall system design.

Neither budget nor schedule is given for testbed development. This TDR includes them to mark the opportunity for substantial risk reduction that they present. This will be most relevant in the case of a NASA-led mission. The eLISA Consortium and ESA have already agreed to produce an engineering qualification model of the eLISA payload by 2020.

2 Technologies

Detection of gravitational waves by the method of Pirani [1956] requires two primary ingredients: an array of inertial reference masses and a measurement system for monitoring changes in the displacement between them. In LISA-like concepts, the displacement measurement is accomplished by a continuous, interferometric laser-ranging system, called the IMS. The inertial reference masses are realized by the free-falling test mass of a drag-free stationkeeping system and a collection of spacecraft design choices, called the DRS in LISA-like concepts. This technology was first demonstrated in 1972 by the Triad mission, and others since then. The LPF mission will demonstrate the approximate disturbance reduction performance and sundry interferometry technologies needed for LISA-like mission concepts.

The technologies required for space-based gravitational wave detection are broadly organized around the IMS and the DRS. Gravitational-wave missions demand tight integration of spacecraft bus and payload. Consequently, although spacecraft stationkeeping and propulsion are not normally considered part of the science instrument, both the thrusters and control laws are included in this roadmap. Three vehicles are required to make the science measurement.

2.1 Telescope Subsystem

Function in the Flight System

The telescope allows a sciencecraft to send and receive light from a remote sciencecraft located approximately a million kilometers away. It has several basic functions:

- expands the outgoing beam from a collimated 5 mm diameter on the optical bench to a collimated beam for transmission to the remote sciencecraft
- collects the light sent from a remote spacecraft and produces a collimated 5 mm beam on the optical bench from the incoming signal
- has an adjustable focus that is used in a set-and-forget mode to keep the telescope input and output collimated from the ground to space, and over time once in space
- relays the input pupil located at the telescope to an output pupil located on the optical bench
- sets an aperture stop for the transmitted beam

See Table 1 for a list of requirements.

A functional block diagram of the design is shown in Figure 1.

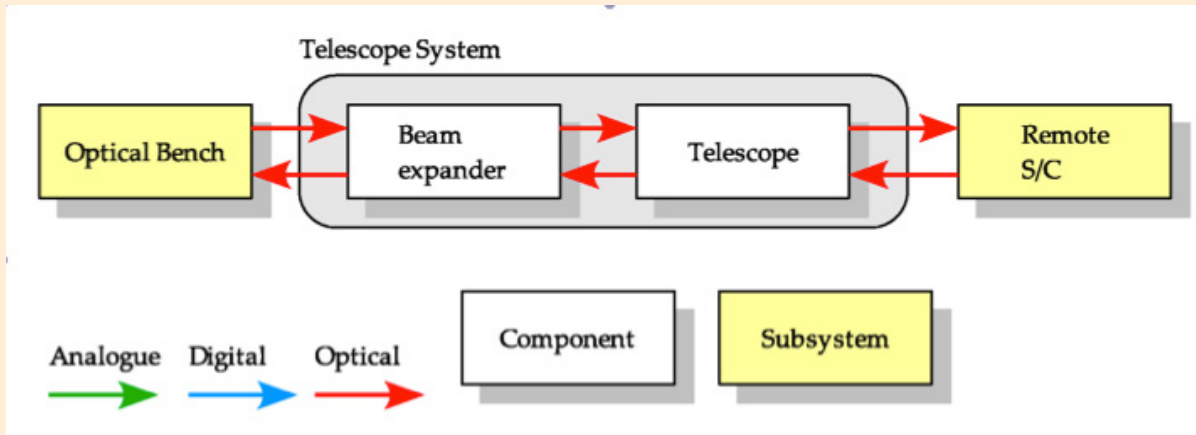


Figure 1: Functional block diagram of the Telescope System.

Baseline Architecture

The telescope design for the LISA baseline mission may be adequately satisfied by a near diffraction-limited classical Cassegrain-style optical system—either on-axis or off-axis. The optical prescription is that of a three-mirror anastigmat (TMA), with a fourth fold mirror. The telescope is mounted on the front of the optical bench in line with the GRS, which is mounted on the rear of the bench.

The basic specifications for the telescope remain essentially unchanged for the different mission variants. In the description that follows, the ESA designs are collectively referred to as “NGO” (New Gravitational-wave Observatory), or “eLISA,” and the NASA designs are referred to as “SGO” (Space-based Gravitational-wave Observatory). The main difference in telescope requirements is the diameter of the telescope aperture. The baseline LISA mission called for a 40 cm aperture. The eLISA design specifies a 20 cm diameter aperture, and the SGO design calls for a 25 cm diameter.

Design option for a NASA-led mission

The baseline orbits require that the entire optical assembly, which includes the telescope, the optical bench, and the GRS, to be articulated to follow the changes in the included angles of each vertex of the triangle over the orbital period of a year. With the SGO drift away orbits, the expected angular variation is small enough that it may be possible to replace the articulation of the entire optical assembly with a small steering mirror that can be moved to track the changes in the included angles. This design option, called in-field guiding, requires a steering mirror that can make an angular change with minimal coupling between the angular motion and any associated optical path length distance change. One immediate benefit to such an implementation is that it would be possible to exchange a laser phase reference between optical benches on different arms within a single spacecraft using a free-space beam instead of a polarization-preserving single-mode optical fiber, reducing a potential noise source and therefore reducing risk.

Requirements and Risks

Key Performance Requirements

The LISA concept telescope, although based on a conventional optical design, is optimized for precision pathlength measurements, so it must be dimensionally stable at the 10^{-12} m/ $\sqrt{\text{Hz}}$ level

under the operating conditions expected for the LISA concept spacecraft, which include low temperatures (-65°C) and temperature gradients, both axial and transverse. Excellent knowledge of the physical properties, particularly the coefficient of thermal expansion (CTE), is also required to maintain alignment tolerances to better than 1 micron. Table 1 shows the nominal performance requirements for both the ESA-led GW mission baseline concept NGO/eLISA and the requirements for the NASA-led mission concept SGO-Mid.

Table 1 – Performance requirements for the ESA LISA Mission variant New Gravitational-wave Observatory (NGO), or eLISA. Specifications #3 and #14 are particularly challenging and specific to the precision measurement application. The main difference between the two designs is the telescope aperture.

	Parameter	Derived From	NGO/eLISA	SGO-Mid
1	Wavelength		1064 nm	1064 nm
2	Net wavefront quality of as built telescope subsystem over science field of view under flight-like conditions	Pointing	$\lambda/30$ RMS	$\lambda/30$ RMS
3	Telescope subsystem optical pathlength* stability under science operations conditions	Pathlength Noise/Pointing	$1 \text{ pm/Hz}^{1/2} \times (1+(0.003/f)^4)^{1/2}$, where $0.001 < f < 1\text{Hz}$ $1 \text{ pm} = 10^{-12} \text{ m}$	$1 \text{ pm/Hz}^{1/2} \times (1+(0.003/f)^4)^{1/2}$, where $0.001 < f < 1\text{Hz}$ $1 \text{ pm} = 10^{-12} \text{ m}$
4	Field-of-View (Acquisition)	Acquisition	+/- 200 mrad	+/- 200 mrad
5	Field-of-View (Science)	Orbits	+/- 7 mrad out-of-plane** +/- 4.2 mrad in-plane	+/- 7 mrad out-of-plane** +/- 4.2 mrad in-plane
6	Transmitted beam diameter (D) on primary mirror	Shot noise/ Pointing	$0.92 \times D$ (primary diameter)	$0.92 \times D$ (primary diameter)
7	Entrance Mirror Diameter	Noise/pointing	200 mm	250 mm
8	Entrance Pupil	Pointing	Entrance of beam tube (or primary?)	Entrance of beam tube (or primary?)
9	Location of image of primary mirror (exit pupil)	Pointing	~14 cm (on axis) behind primary mirror	~14 cm (on axis) behind primary mirror
10	Pupil distortion	SNR	10%	10%
11	Beam size on bench	Short-arm interferometer	5 mm	5 mm
12	Mechanical length		350 mm	350 mm
13	Optical efficiency	Shot noise	>0.85	>0.85
14	Scattered Light	Displacement noise	$< 10^{-10}$ of transmitted power	$< 10^{-10}$ of transmitted power

Table 1 Notes:

*Optical pathlength is the net total pathlength through the telescope as experienced by either the transmitted or received beam, which can be defined as the accumulated phase divided by the wavenumber ($2\pi\lambda$).

**Out-of-plane or in-plane refers to two orthogonal spatial directions in the telescope. The final application for these telescopes involves mounting them in three spacecraft that form an equilateral triangle that is in the same orbit as the Earth about the sun, but lagging by 22 degrees in orbital phase. The plane of the triangle is inclined at 60 degrees from the ecliptic. In-plane refers to the plane of this triangle, and out-of-plane is normal to it.

The two main challenging requirements for the telescope design are: 1) the requirement for dimensional stability at the picometer/ $\sqrt{\text{Hz}}$ level for the primary-to-secondary mirror spacing in the presence of both axial and transverse temperature gradients, and; 2) the requirement for low stray light levels. Stray light levels must be extremely low because the distance measurement is made using interferometric techniques that are very sensitive to low light levels and, also, because the telescope is used to transmit a one-watt beam and receive a 100-picowatt beam simultaneously. The typical imaging application for a telescope does not have these requirements.

The telescope technology study effort will develop a set of suitable requirements for the LISA metrology application and investigate these two key design challenges.

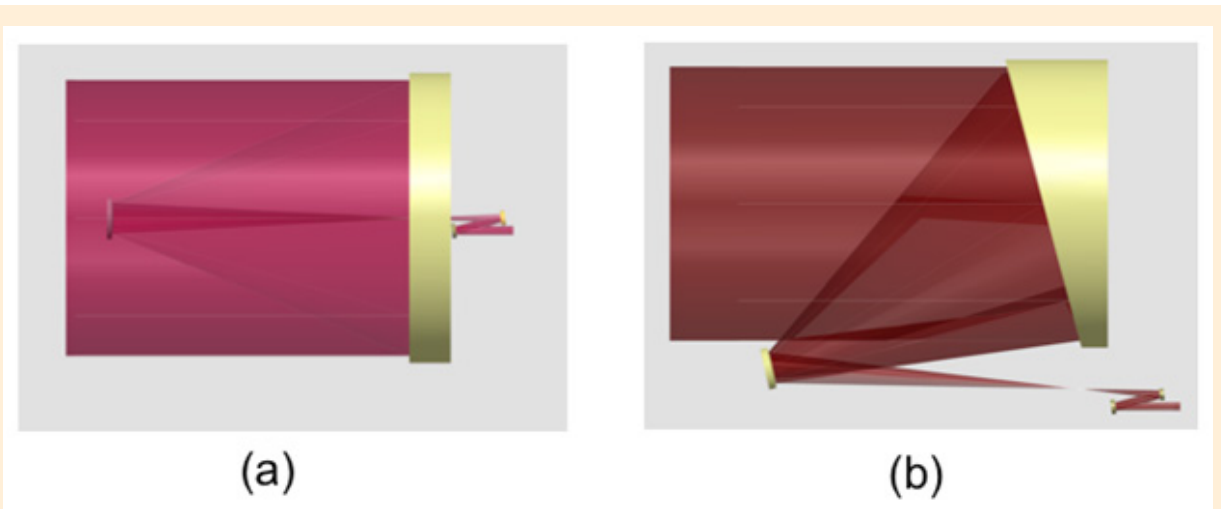


Figure 2: Left: NGO on-axis Cassegrain design. Right: NGO off-axis Cassegrain design.

The left-hand image in Figure 2 shows a solid model of the optical path of a nominal 20-cm aperture on-axis Cassegrain design suitable for the ESA-led NGO mission. The right-hand image in Figure 2 shows an off-axis Cassegrain design with the same optical prescription as in the left-hand image, indicating that both designs are similar in conception. Both are based on a three-mirror anastigmat (TMA) design with a fourth folding mirror.

Risks

The main technical risk identified to date is contamination (other than meeting the two challenging specifications of stray light performance and dimensional stability). Since the integration and test phase with the spacecraft may take up to two years, it will be important to maintain cleanliness without becoming a cost driver. Several contamination mitigation strategies exist, including keeping the optics bagged and under a clean low-pressure purge environment, applying a protective coating, or using a cover.

A common practice with telescopes is to include a cover that is put on after testing and kept in place through launch until the telescope is ready for commissioning. A cover will require an extremely reliable and low-impact actuation mechanism. Several candidate actuators exist, and will be part of a trade study once a realistic reliability study is done for the mission at a systems engineering level.

A further risk is that the telescope may well be one of the coldest surfaces in the spacecraft, so some care must be taken to make sure that the optics do not function as a getter and actually pump contaminants onto the surface.

Another risk that has been identified is the manufacturability of the design. An off-axis design would normally be the preferred choice because the lack of a central obstruction increases the optical efficiency and reduces stray light effects. However, a preliminary tolerance analysis performed prior to this study indicates that the design is very difficult to build in a normal optical shop. This is a risk because we need six flight units and several for ground testing—approximately 10 telescopes total. A robust design is necessary to be sure that the fabrication of the telescopes is not an undue schedule risk, and also to allow the telescopes to be interchangeable so replacing a telescope does not require realignment from scratch. Additionally, the expected thermal environment has both an axial and a transverse temperature gradient, so environmental effects would naturally tend to create off-axis aberrations. An on-axis design generally has better resistance to these environmental effects, but the on-axis spot in the center of the secondary mirror causes unacceptably high levels of scattered light. Therefore, the best design choice is not clear and requires further study.

Status

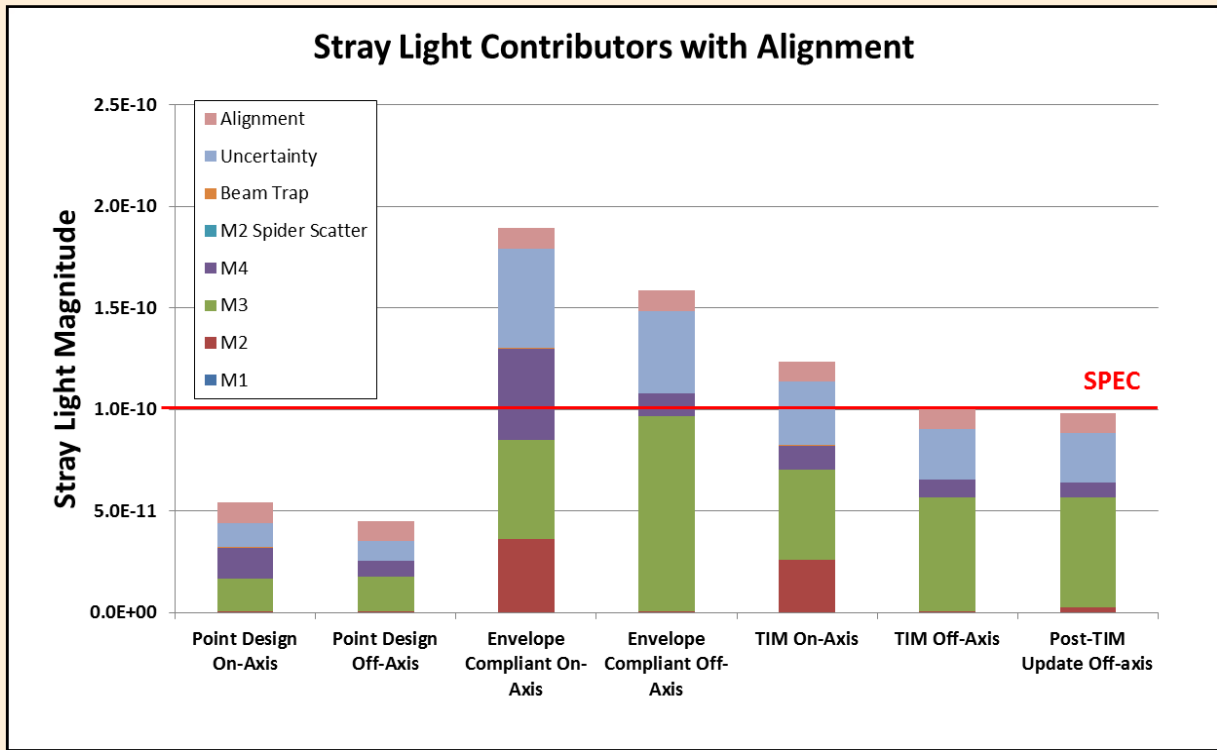
TRL of Subassemblies

A silicon carbide telescope spacer has been shown to meet the dimensional stability requirements at room temperature [1]. At the operating temperature of -65°C , stability was limited by thermal fluctuations in the test chamber. When these measured fluctuations are removed from the data, the stability meets requirements (No. 3 in Table 1) at the operating temperature. These results represent a TRL of approximately 4+ for the metering structure. Design and testing of a complete telescope is in progress as described in the next few paragraphs.

Stray Light Study Results

A stray light analysis has been started using the commercial non-sequential ray-tracing package FRED. The analysis has focused on developing a model of the on-axis eLISA telescope, including obstructions, based on the optical prescription, a mechanical model, and some simplified assumptions for surface roughness and cleanliness for materials and coatings. We used the University of Glasgow design [3] for the LISA optical bench to locate the detectors and field

stops, and have been plotting the ratio of power delivered to the output of the telescope divided by power scattered onto the detectors for several treatments of the on-axis region of the secondary mirror: a hole in the mirror, a region blackened with carbon nanotubes, and a phase mask designed to reduce on-axis scatter. Figure 3 shows preliminary results for an off-axis design that meets requirements.



Post – TIM Model	
Contributor	Straylight
M1	< 5.0E-14
M2	2.43E-12
M3	5.43E-11
M4	7.32E-12
Uncertainty	2.41E-11
Alignment	1.00E-11
Total	9.82E-11

Figure 3: Stray light scattered onto the main science detector from an off-axis telescope. The requirement is 10^{-10} . The primary is M1, secondary is M2, etc. (see Figure 1). The largest stray light contributor is the third mirror, M3.

Other Development Activities

Work on a telescope in Europe was funded through an industrial Invitation To Tender (ITT) process and has concentrated on an off-axis design using Carbon Fiber Reinforced Polymer (CFRP) as the structural material. Results [4] for the dimensional stability characterization of an off-axis metering structure have recently been reported. The measured stability of the test is approximately $10,000 \text{ pm}/\sqrt{\text{Hz}}$ at 1 mHz, subject to a variety of noise sources in the measurement setup. The basic interferometer stability is just under $100 \text{ pm}/\sqrt{\text{Hz}}$ at 1 mHz, and reaches $\sim 2 \text{ pm}/\sqrt{\text{Hz}}$ for frequencies above $\sim 0.07 \text{ Hz}$. The CFRP formulation tested had a measured CTE of $-3.1 \times 10^{-7}/\text{K}$ at 30°C , approximately two orders of magnitude higher than predicted, again limited by noise sources in the measurement facility.

In the U.S., research at the University of Florida has studied scattered light from a Cassegrain telescope [5] using Fast Fourier Transform (FFT) techniques and concluded that it should be possible to achieve scattered light performance sufficient to achieve $10^{-6} \text{ cycle}/\sqrt{\text{Hz}}$ phase measurement accuracy by suppressing the on-axis reflection from the secondary mirror and using polarization optics.

Development Tasks to TRL-5

ESA-led Scenario

For the scenario in which the space-based mission is ESA led, the proposed near-term development activities are to focus on demonstrating the key requirements with a prototype telescope, first under laboratory conditions and then under flight-like environmental conditions. The specific activities are as follows:

- 1) Complete a requirements study to develop straw-man NGO specifications and kick off a study with an aerospace industrial partner to validate the design, including a detailed tolerance analysis and an assessment of manufacturability. For FY13, this study would continue on to procure a first prototype optical design that could be used for testing.
- 2) Continue studying scattered light reduction techniques by updating an existing LISA baseline model for NGO requirements and finish a promising anti-scattering mask design. In parallel, begin to make measurements on representative substrates to test different techniques for reducing scattered light, including a strategically placed and shaped hole, anti-reflection coatings, and blackening coatings made with carbon nanotubes with a proprietary process invented at GSFC.

These activities are a continuation of work begun in FY11. Note that the telescope spacer study, a technology development project not funded by PCOS internal resources in FY12, has already demonstrated that silicon carbide is a suitable structural material for the metering structure of a telescope and meets the stability requirements of a LISA-like mission precision metrology application. Some of the results of that work were published this year in [1].

Key challenges and innovations

The key challenge is to compare an on-axis design, which is more stable for the expected thermal environment, less expensive to build and test, but expected to have higher stray light levels against an off-axis design that has better stray light performance but is expected to be much more difficult to build. The key question is whether or not an on-axis design can meet the stray light requirements. Alternatively, a demonstrated capability for small-scale production of off-axis telescopes that meet requirements would also be an acceptable outcome because it would mean that the expected tolerance and fabrication tolerance issues for an off-axis design could be overcome.

NGO/eLISA design

A first-order design for the ESA-led NGO (or eLISA) mission with both an on-axis and off-axis version with the same nominal prescription that nominally meets specifications by design has been completed. The eLISA “Yellow Book” document [2] was used as a guideline for developing the specifications. A preliminary mechanical design for the on-axis version has been completed (Figure 4) and includes a space-qualified focus mechanism. Further analysis is needed, including a tolerance analysis of both optical designs.

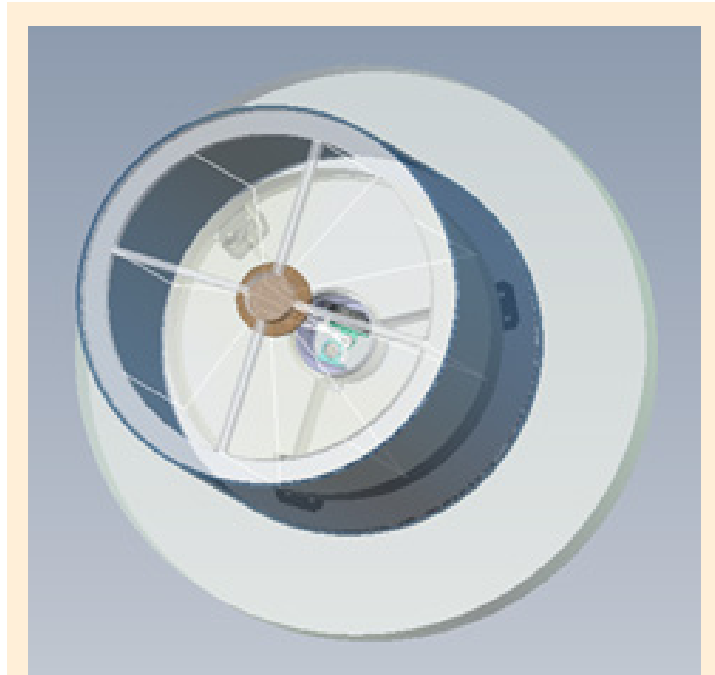


Figure 4: Mechanical model of the on-axis eLISA telescope design showing the spider and tertiary mirror. The telescope is mounted on a strongback that supports the optical bench and gravitational reference sensor.

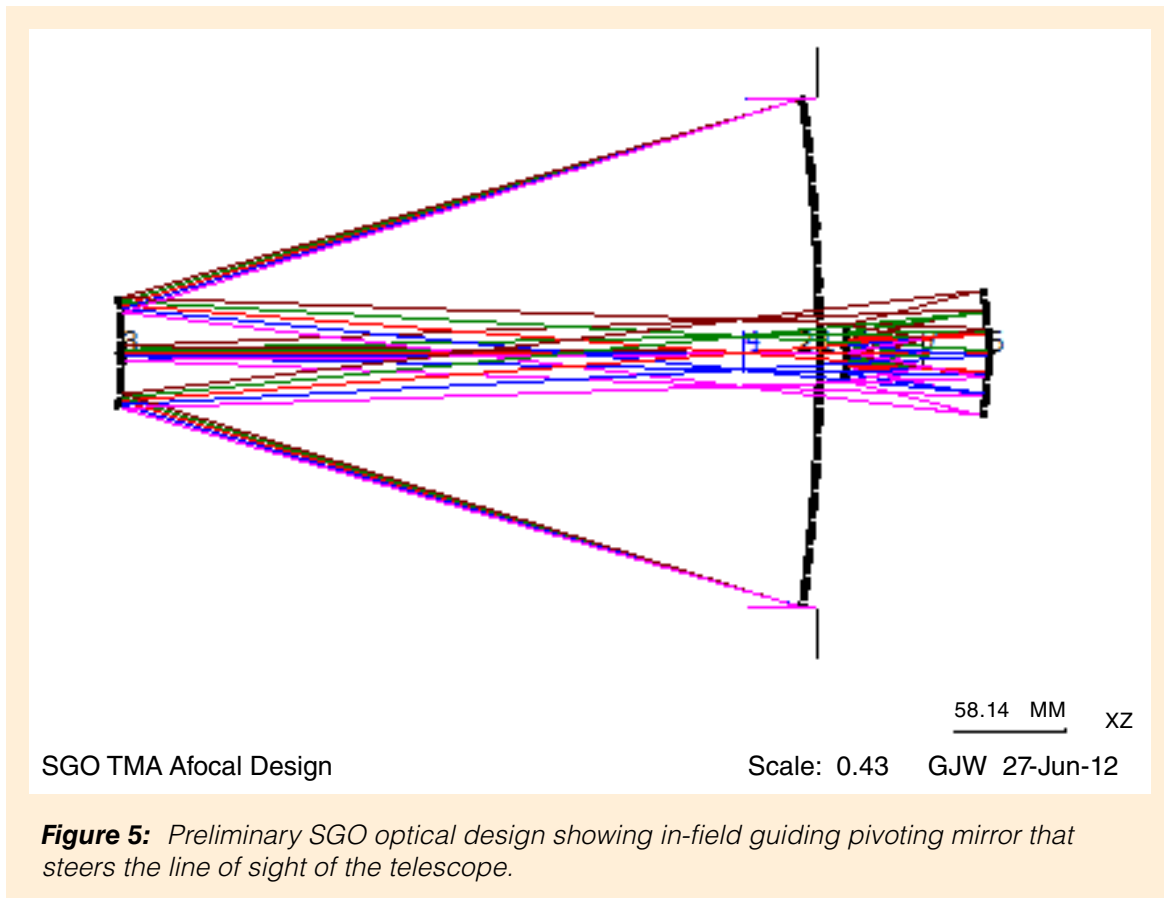
NASA-led Scenario

The initial development activities for NASA-led mission are identical to the scenario described for an ESA-led mission under an L2 cornerstone gravitational-wave theme. There are some differences in the design tradespace to be explored, described below, and there is additional time for development after the first prototype is tested. This time will be used to investigate the in-field guiding design option.

SGO in-field guiding design option

A first-order design for an on-axis telescope has also been completed for the NASA SGO family of mission concepts (Figure 5). As the constellation of spacecraft move in their orbits, the angles formed between the legs of the triangle vary slightly from the nominal 60 degrees that they would subtend if the triangle were perfectly equilateral. The variation in angle is larger than the field of view of the telescope, so it is necessary to move the telescope line of sight to follow. The SGO orbits allow for the possibility of an “in-field guiding” design that uses a pivoting mirror inside the telescope to steer the optical axis of the telescope and eliminate the need to move the entire

telescope and optical bench assembly on a pivot. The large variation in the angles between spacecraft for the ESA eLISA mission constellation makes in-field guiding not practical for those missions because the required pivoting motion of the steering mirror is too large. A mechanical design for the SGO on-axis telescope is in process, but accommodation of the focus mechanism and additional relay optics required by the in-field guiding design have required iteration of the optical design to increase mechanical clearances while retaining the optical performance.



Immediate next steps/funded development

Under the existing task, there are two main immediate next steps for the telescope work to be accomplished in Calendar Year 2013 (CY13). The first step is the completion of the industrial study to validate the telescope design, including a detailed tolerance analysis and an assessment of manufacturability (see the discussion in the Objectives section above for more detail). The study contract was awarded in November 2012 and results were delivered in April 2013. The recommended design is silicon carbide off-axis design.

The second step is further progress on the study of stray light. Initial results for a hole in the secondary mirror show that stray light levels on the main science detectors are approximately 30 pW for 1W of transmitted power, which is nominally acceptable. However, the model must be extended to include diffraction and polarization, and we need to consider an apodized mask design as well. The mask design work is in progress, with the first step to validate the model against measurements to be sure that the models are correct and that they include all relevant effects. We expect results by September 2013.

There are two clear steps for future telescope work beyond the end of the calendar year. The first is to continue the stray light analysis and start the experimental measurements of scattered light suppression techniques as just discussed, and the second is to actually fabricate and test a prototype telescope to verify that the design can meet requirements and that it is indeed possible to manufacture with reasonable optical shop practices.

Three tasks have been defined for this follow on work:

Task 1: Optical pathlength stability in a relevant environment. This would build on the work done to demonstrate a silicon carbide telescope spacer element, but for the complete telescope including optics.

Task 2: Stray light suppression.

Task 3: Manufacturability study and preliminary demonstration.

Table 2 shows the proposed work plan for these tasks, taken from the SAT proposal described in the next section.

Table 2—Work Plan Milestones Funded by the SAT Proposal

Task Description	Activities	Duration (mos)
Tasks 1 and 3		
Telescope Procurement	Specify requirements based on study results	18
GSFC Design Study	In-house simplified design	9
Measurements	Commercial Telescope	6
Task 2		
Modeling	Update scattered light model	8
Measurements	Fabricate and measure binary masks. Verify performance against model	12

Table 3—Milestone Summary Schedule from the SAT Proposal

Year	Milestone	Date	Milestone Description	Success Criteria
FY13	1	9/13	Stray light measurement capability	Demonstrated dynamic range of 10^{-10} per Table 1
FY14	2	3/14	Demonstration of low stray light	$< 10^{-10}$ of transmit power per Table 1
FY14	3	9/14	Demonstration of optical pathlength stability	1 pm/ $\sqrt{\text{Hz}}$ requirement per Table 1

Table 4—Summary of Funding Awarded for Telescope Development through FY14

	FY13	FY14	Total
Funding (\$k)	\$417.5	\$495.4	\$912.9
FTE	2.92	3.05	5.97

At the end of Fiscal Year 2014 (FY14), successful completion of the development work outlined here will result in a prototype telescope subsystem tested for the main requirements, including dimensional stability and scattered light performance, under laboratory conditions simulating the relevant environment and with laboratory interfaces. This is the definition of TRL 4.

Further Development to reach TRL-5

Plans for development beyond the currently funded development to advance the telescope to the TRL-5 level are less well developed. Here is a general outline of what will be required under an ESA-led scenario.

Table 5— Summary of tasks, people, duration, and funding to take the telescope design from TRL-4 to TRL-5 under an ESA-led scenario

ESA-Led							
Task ID	Task Description	Duration (mo)	Dependencies	Resources		TRL	
				FTEs	Procurement (\$k)	In	Out
1	Prototype Telescope Modifications	9		1	800	4	5
1.1	Update optical design	2	None	0.3	200		
1.2	Update mechanical design	1	Complete 1.1	0.2	100		
1.3	Procurement	6	Complete 1.1, 1.2	0.5	500		
2	Realistic Interfaces	6	None	2.5	500	4	5
2.1	Optical bench and detectors	6	None	1	200		
2.2	GRS simulator	6	None	1	200		
2.3	Laser source	6	None	0.5	100		
3	Measurements	15	Complete 1, 2	2.5	2500	4	5
3.1	Optical testing	3	Complete 1, 2	0.5	500		
3.2	End-to-end stability	6	Complete 3.1	1	1000		
3.3	Stray light	6	Complete 3.2	1	1000		

Task ID	Description	FY14												FY15													
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep		
1	Prototype Telescope Modifications	[Task 1: Oct FY14 to Jul FY14]																									
1.1	Update Optical Design	[Task 1.1: Oct FY14 to Nov FY14]																									
1.2	Update Mechanical Design			[Task 1.2: Dec FY14 to Jan FY15]																							
1.3	Procurement			[Task 1.3: Dec FY14 to Jul FY15]																							
2	Realistic Interfaces	[Task 2: Oct FY14 to Mar FY15]																									
2.1	Optical Bench and Detectors	[Task 2.1: Oct FY14 to Mar FY15]																									
2.2	GRS Simulator	[Task 2.2: Oct FY14 to Mar FY15]																									
2.3	Laser Source	[Task 2.3: Oct FY14 to Mar FY15]																									
3	Measurements										[Task 3: Jul FY14 to Sep FY15]																
3.1	Optical Testing										[Task 3.1: Jul FY14 to Sep FY14]																
3.2	End-to-End Stability										[Task 3.2: Oct FY14 to Mar FY15]																
3.3	Stray Light																[Task 3.3: Mar FY15 to Sep FY15]										

Figure 6: Telescope, ESA-led.

For a NASA-led scenario, the goal is to be at TRL-5 by CY2018, an additional two years for development beyond the ESA-led scenario. Some of this additional time would be spent developing an in-field guiding design. Table 6 outlines development tasks for this scenario.

Table 6— Summary of tasks, people, duration, and funding to take the telescope design from TRL-4 to TRL-5 under an NASA-led scenario

NASA-Led							
Task ID	Task Description	Duration (mo)	Dependencies	Resources		TRL	
				FTEs	Procurement (\$k)	In	Out
1	In-field Guiding Design	14		2.5	1200	4?	?
1.1	Optical design	2		0.2	100		
1.2	Mechanical design	2	Complete 1.1	0.3	100		
1.3	Actuator development	6	Complete 1.2	1	600		
1.4	Actuator testing	6	Complete 1.3	1	400		
2	Prototype Telescope Modifications	9		1	800	4	5
2.1	Update optical design	2	None	0.3	200		
2.2	Update mechanical design	1	Complete 2.1	0.2	100		
2.3	Procurement	6	Complete 1.1, 1.2	0.5	500		
3	Realistic Interfaces	6	None	2.5	500	4	5
3.1	Optical bench and detectors	6	None	1	200		
3.2	GRS simulator	6	None	1	200		
3.3	Laser source	6	None	0.5	100		
4	Measurements	15	Complete 1,2	2.5	2500	4	5
4.1	Optical testing	3	Complete 1,2	0.5	500		
4.2	End-to-end stability	6	Complete 4.1	1	1000		
4.3	Stray light	6	Complete 4.2	1	1000		

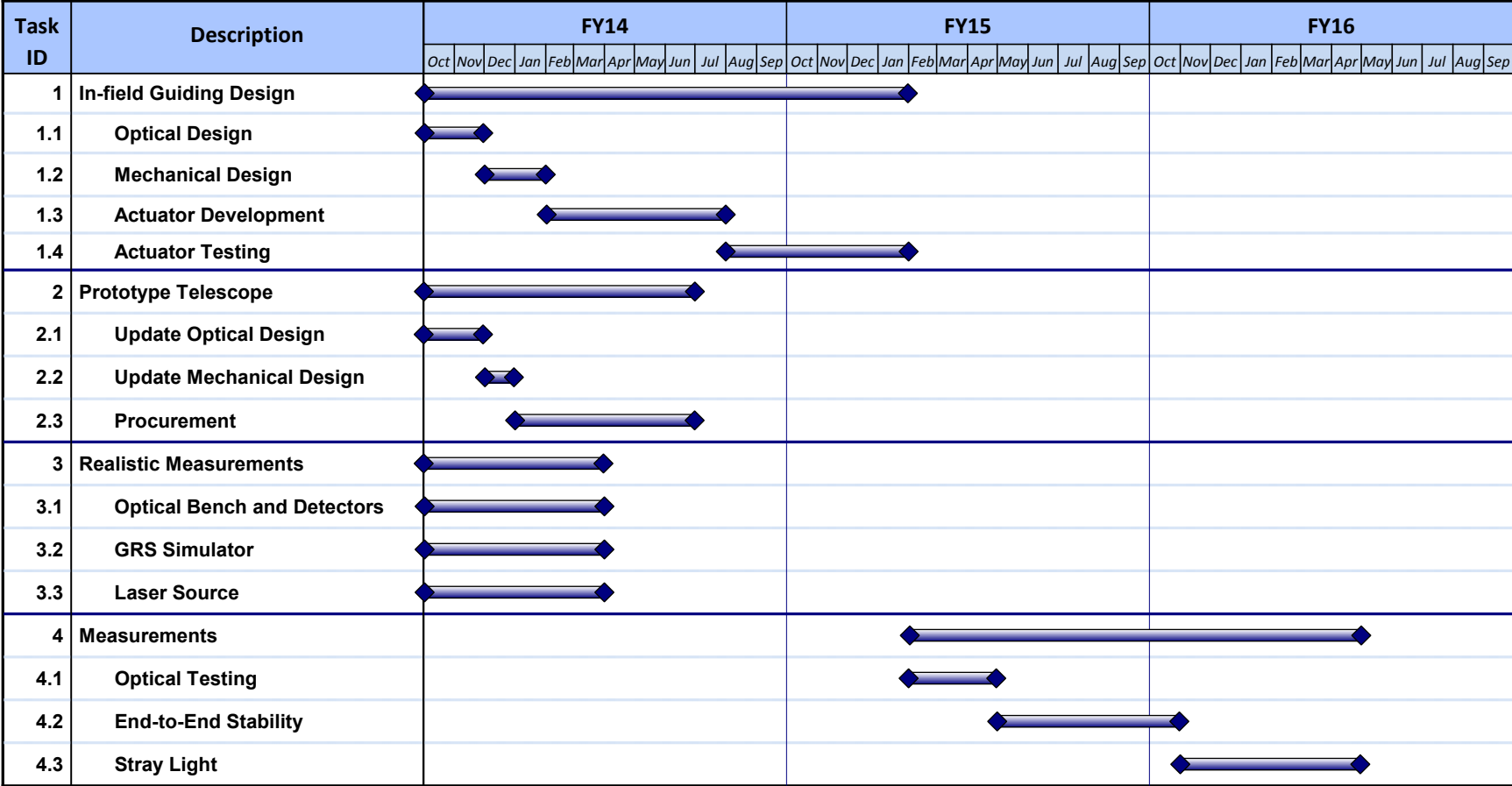


Figure 7: Telescope, NASA-led.

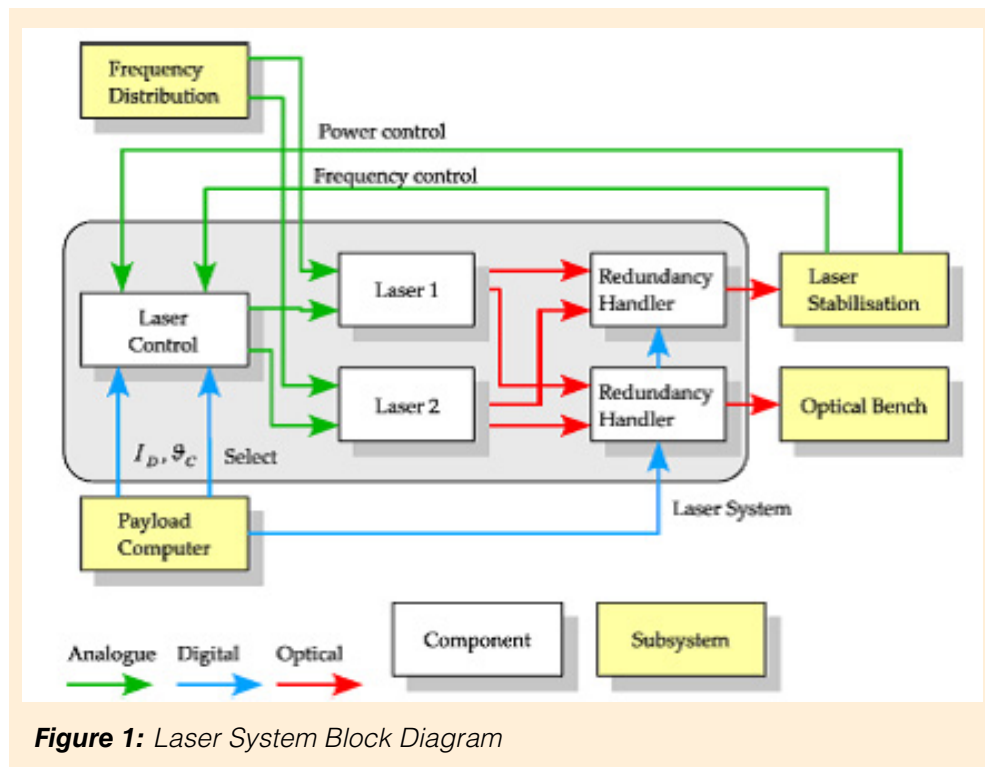
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- [5] Spector, A. and Mueller, G., Back-reflection from a Cassegrain telescope for space-based interferometric gravitational-wave detectors, 2012 *Class. Quantum Grav.* 29 205005 doi:10.1088/0264-9381/29/20/205005

2.2 Laser Subsystem

Subsystem Function in the Flight System

The purpose of the laser for the eLISA baseline space-based gravitational-wave observatory missions is to provide the stabilized light source that interferometrically monitors the spacecraft separation with a precision of 10^{-12} m (1 pm) over several million kilometers at a timescale of 10^3 sec. The laser is frequency and amplitude stabilized, and also phase modulated to provide clock tones for spacecraft synchronization. A diagram of the laser system and its interfaces to the eLISA mission is shown in Fig. 2. Technology development for a GW laser is a top priority technology need recommended by the PCOS Technology Management Board (TMB) in 2011 and 2012.¹



Baseline Architecture

The laser design pursued in Europe for the eLISA baseline mission is a commercially supplied NRPO laser, followed by a commercially supplied amplifier. This forms the so-called MOPA architecture. Both the oscillator and amplifier are supplied by a single vendor: TESAT, the German telecommunications company. The outstanding issues are verifying the performance of the TESAT amplifier, including differential phase noise, and verifying the performance of the full laser system. The goal is TRL 5 by 2015.

At NASA we are developing a MOPA architecture, but it will use an External Cavity Laser (ECL), followed by a power amplifier built at Goddard. As we describe in detail below, this design has numerous advantages, including simplicity, compactness, robustness, and transparency. The design is shown in Fig. 2.

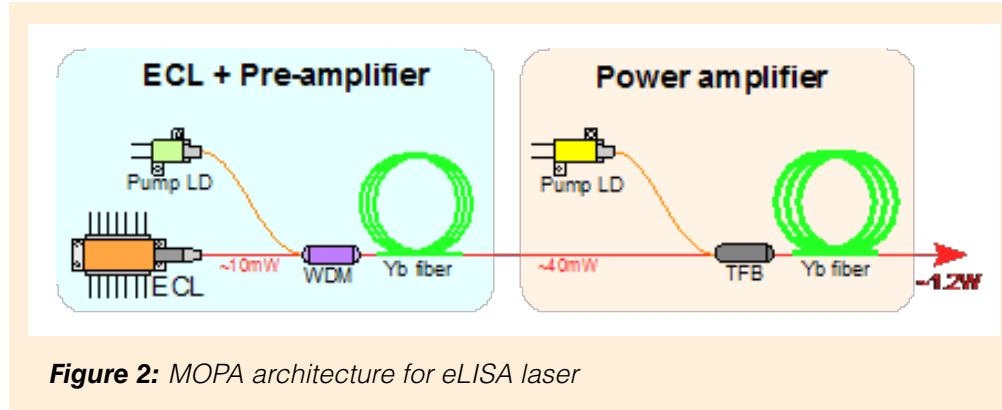


Figure 2: MOPA architecture for eLISA laser

The basic specifications for the laser remain essentially unchanged for the different mission variants. In the description that follows, the ESA designs are referred to as “eLISA,” and the NASA designs are referred to as the Space-based Gravitational-wave Observatory (SGO). The laser will provide 2 Watts of output power, stabilized to the levels indicated in Table 1 below, for both eLISA and SGO.

Key Performance Requirements

The LISA laser system requirements involve the power, mode shape, and stability of the laser light. The stability requirements include amplitude noise, frequency noise, and differential phase noise (i.e., the relative phase noise between carrier and sideband frequencies.) The requirements are listed in Table 1.

Table 1—Laser Performance Requirements

	Parameter	Frequency Band	eLISA	SGO-Mid
1	Wavelength		1064 nm	1064 nm
2	Laser Output Power (EOL)		1.2 Watt	0.8 Watt
3	Frequency Noise	10^{-3} Hz	$100 \text{ Hz}/\sqrt{\text{Hz}}^{1/2}$	$100 \text{ Hz}/\sqrt{\text{Hz}}^{1/2}$
4	Relative Intensity Noise	10^{-3} Hz 10^7 Hz	$10^{-4}/\sqrt{\text{Hz}}$ $10^{-8}/\sqrt{\text{Hz}}$	$10^{-4}/\sqrt{\text{Hz}}$ $10^{-8}/\sqrt{\text{Hz}}$
5	Differential Phase Noise	10^{-3} Hz	$6 \times 10^{-4} \text{ cycles}/\sqrt{\text{Hz}}$	$6 \times 10^{-4} \text{ cycles}/\sqrt{\text{Hz}}$
6	Lifetime		2 years	2 years

Risks

The main technical risk identified to date is lifetime of the laser diodes. This will be studied with accelerated aging tests, on both the amplifier pump diodes and the oscillator laser chip. Other risks that are addressed with this technology plan include oscillator phase noise; oscillator reliability under thermal cycling and radiation; amplifier lifetime; and amplifier noise from stimulated Brillouin scattering.

Current Status

1. Oscillator: External Cavity Laser (ECL)

After examining the field of low-noise lasers, we identified a compelling candidate for the GW oscillator: the ECL, built by Redfern Integrated Optics (RIO)³. The ECL is comprised of a 400 μm size laser gain chip, integrated to a Bragg reflector etched into a planar silicon waveguide. The present commercial device wavelength is 1550 nm; an ECL redesign for 1064 nm is under way in a Small Business Innovation Research (SBIR) contract and is discussed below.

The Telecordia-qualified 15 mW ECL offers numerous advantages relative to solid state lasers, including simpler design, more compact size, lower mass, and consumption of less electrical power. Fig. 3 shows a schematic of the ECL, and a comparison of its size with the NPRO, a commonly used low-noise laser.

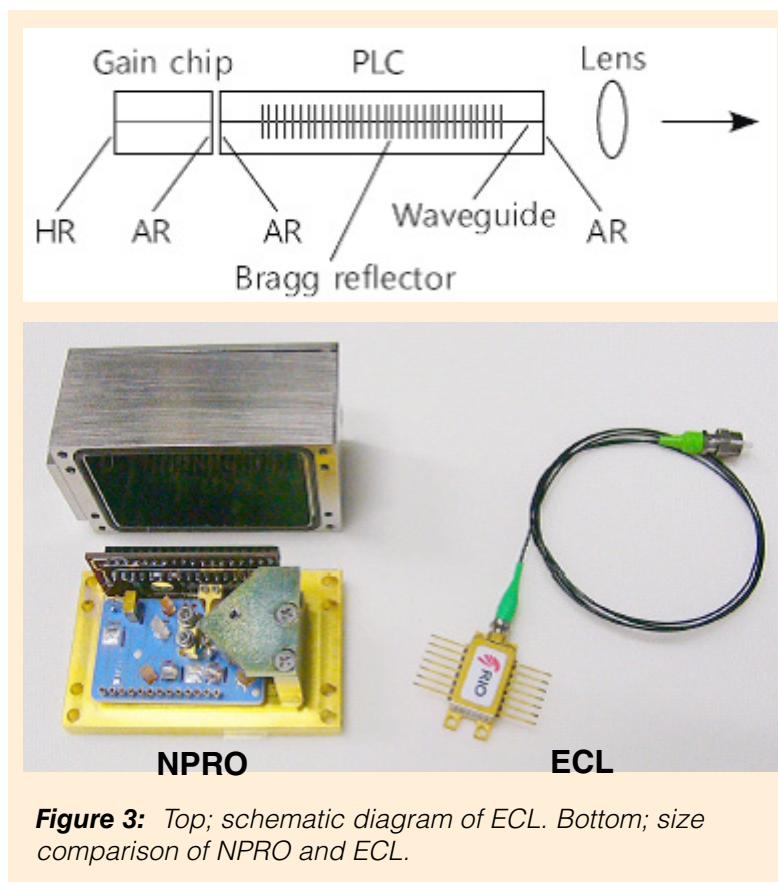
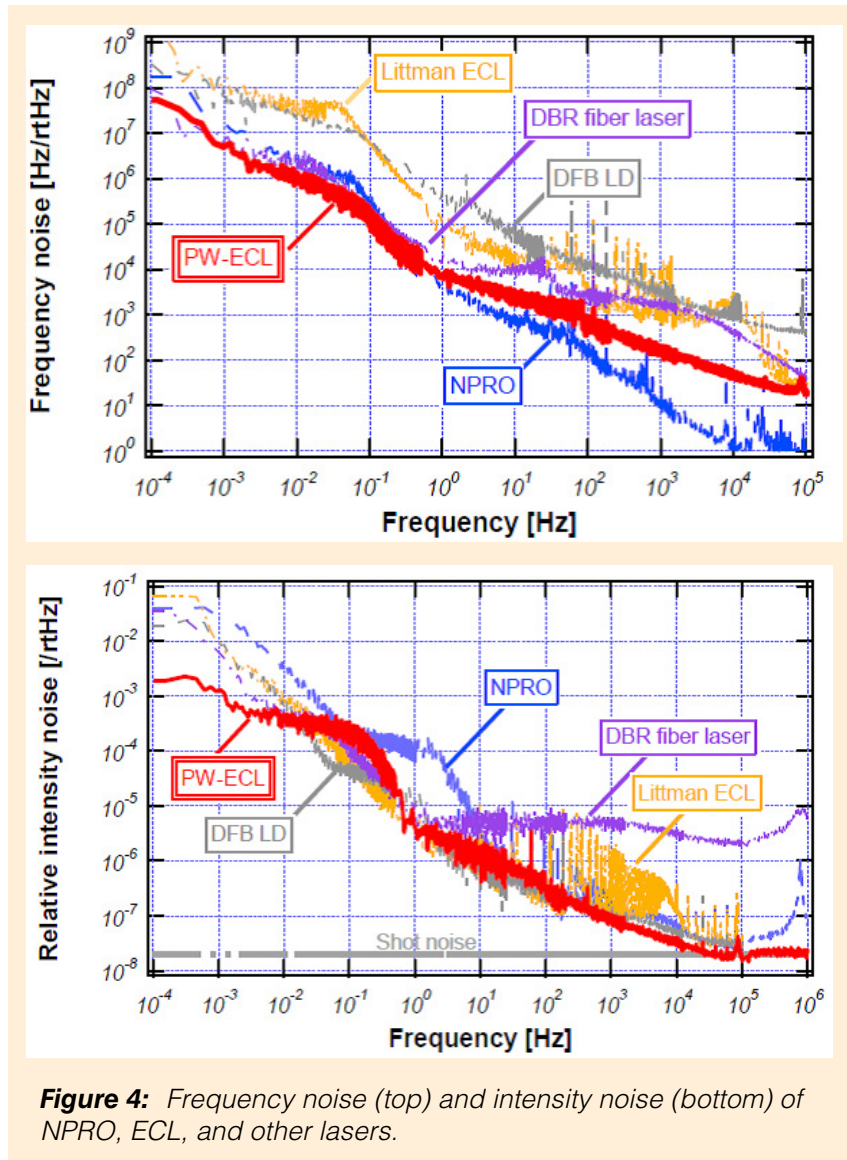


Figure 3: Top; schematic diagram of ECL. Bottom; size comparison of NPRO and ECL.

Our choice of the ECL was informed by an investigation⁴ of a number of lasers developed for the telecom industry, including the distributed feedback (DFB) laser diode, the distributed Bragg reflector (DBR) fiber laser, and the ECL. The performance of these lasers is shown in Fig. 4.



Demonstration of 1550 nm ECL Space Qualification

We have performed a detailed study of the mechanical, thermal and radiation robustness of the 1550 nm ECL, and have determined it to be space qualified. Most of these tests probe the ECL packaging, which will not change in the 1064 nm redesign discussed below. The tests done included vacuum thermal cycling, hermiticity testing, radiation testing⁵, and accelerated aging of the laser chip.

The low mass, simplicity, noise performance, and mechanical and thermal robustness of the ECL make a compelling argument for its use in a GW laser. For these reasons, the 1550 nm ECL has recently been adopted as the metrology laser for the OpTIIX mission on the ISS.

Development of 1064 nm ECL

Through an SBIR contract, RIO has undertaken the development of the 1064 nm ECL—the Principal Investigator (PI) of this proposal is also Contracting Officer Technical Representative (COTR) of the SBIR contract). This has involved 1) replacing the 1550 nm InP/InGaAsP quantum well structure with GaAs/InGaAs, to support operation at 1064 nm, and 2) modifying the coatings, Bragg reflector and waveguide for operation at 1064 nm. The current status of this effort is: all key components have been designed; the low noise multi-quantum well structure for the laser gain chip has been developed; and a 345 nm lithography technique has been developed for the waveguide Bragg grating. The first 1064 nm ECL prototypes were delivered to GSFC for detailed noise characterization in April, 2013.

2. Construction and Noise Measurements of Laser Amplifier Prototype

Under contract with Goddard, Lucent Government Services built an eLISA Yb fiber amplifier prototype (Fig. 5.) A 10- μm core, double-clad, large mode area gain fiber was selected to maximize the threshold for SBS (stimulated Brillouin scattering). The length of the clad-pumped gain fiber was about 5 m. The 10- μm -diameter fiber is coupled to the rest of the amplifier's nominal 6- μm fiber through a tapered splice.

A 976-nm pump laser diode was selected for its high efficiency and low noise figure. The amplifier was designed to be polarization maintaining, with a polarization extinction ratio (PER) of ~ 20 dB. The single-stage design gives 2 W output with 40-mW seed laser input and 5-A pump current on the fiber-coupled 10-W pump laser diode ($\sim 60\%$ optical-to-optical efficiency).

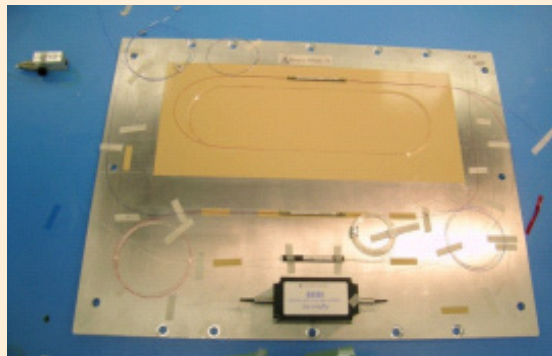
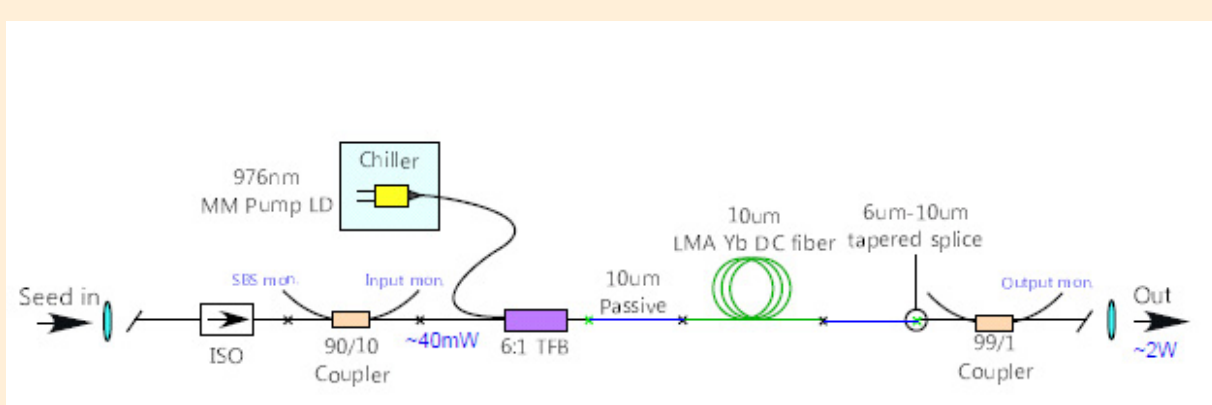


Figure 5: Schematic (top) and photo (bottom) of an amplifier prototype showing pump diode, gain fiber, and isolator.

Amplifier Frequency and Intensity Noise: The frequency noise of the amplifier was measured by using an NPRO laser as the seed, and by comparing the output to an additional frequency stabilized NPRO laser. The noise was seen to be negligible above the NPRO seed noise. The amplifier intensity noise was measured with a stable photodetector and suppressed with a 10 kHz servo which controlled the current to the amplifier pump diode. The noise met the eLISA requirements at 10^{-3} Hz, but has an excess of a factor of ~ 10 around 10^{-4} Hz, believed to be due to temperature variation at the photodiodes.

Amplifier Differential Phase Noise: A signal picked off before the amplifier was used to phase-lock two lasers at frequency offset of 2 GHz + 2 MHz. This signal was also mixed with the amplifier output using the 2 GHz reference. The difference in phase noise between the amplified carrier and 2 GHz sideband, at 2 MHz, was within a factor of three of eLISA requirements. This excess was due to temperature variation.

Stimulated Brillouin Scattering (SBS): SBS is a key noise mechanism in high-power laser amplifiers. Resulting from phonon excitation in the fiber, it may cause excess intensity or differential phase noise, or even a catastrophic failure of the fiber through unexpected lasing. We have undertaken a careful study of the threshold for SBS generation in the amplifier, by examining the light backscattered from the gain fiber as a function of the optical gain. A threshold appears around 1.6 Watts (W) out, close to the required output power.

Amplifier Reliability: Thermal Cycling and Gain Fiber Irradiation

As a first look at the amplifier reliability, we performed vacuum thermal cycling and gain fiber irradiation. Thermal cycling in vacuum can uncover amplifier mechanical problems, including the integrity of the splices between the two different diameter fibers. Very small variances in power and extinction ratio PER (a sensitive measure of mechanical stress) were likely due to coupling from the pump diode to the gain fiber and the dependence of PER on temperature, respectively. Tests over week-long timescales gave similar results. We also looked at the effect of gamma irradiation on the gain fibers, from three different vendors with an accelerated exposure of 60 krad over 5 hours. The data identified the fiber from the vendor Liekki as showing low enough loss to be acceptable for space.

Current TRL of Laser Components

Table 2 summarizes the current TRL of the laser oscillator and amplifier.

Table 2—Current TRL of the Laser Oscillator and Amplifier

Component	TRL	Comments
1064 nm ECL	3	A 1064 nm prototype ECL oscillator has been constructed and is now operational at RIO. It is within a factor of 10 of phase noise requirements.
Laser Amplifier	4	A 2-W laser amplifier was constructed at LGS and characterized at GSFC. It meets most noise requirements and has been thermal vacuum cycled and radiation tested.

Development Tasks to TRL-5

In this section we describe the proposed work to reach TRL 5 for the full laser system. This will involve two steps: first, the final noise and reliability testing of the separate oscillator and amplifier, and then the demonstration of the full TRL 5 performance of the combined stabilized oscillator/amplifier system.

1. Noise Measurements and Characterization of 1064 nm ECL Oscillator

RIO delivered the first 1064 nm ECL prototypes for us to characterize around May 2013. We found that it had acceptable intensity noise, but its phase noise was a factor of 10 higher than the 1550 nm version. This will be addressed by optimizing the design of both the gain chip and the optical cavity, and will require ~\$250k funding for RIO development.

2. Final Reliability Testing of 1064 nm ECL Oscillator

After the oscillator wavelength change has been achieved, its reliability for space operation will be demonstrated. As described above, the reliability testing of the 1064 nm oscillator will include vacuum thermal cycling, hermiticity tests, radiation exposure, and accelerated aging tests of the laser gain chip. Since the packaging of the ECL will remain essentially the same in the transition to the 1064 nm wavelength, the vacuum thermal cycling and hermiticity tests are expected to be minimal risk. The laser chip radiation and accelerated aging tests will be done on a new material so there is some uncertainty; however, GaAs/InGaAs is a well-known, well-tested material in the laser industry so again problems are not expected. A total of \$400k will be used in the final 1064 nm oscillator reliability testing.

3. Rebuild of Laser Amplifier

The amplifier will be rebuilt to incorporate the following features (Fig. 6). A short (3 m) length Liekki gain fiber will be used to raise the SBS threshold; a defined output port including pump light and ASE filter, optical isolator, and beam collimator will present the cleanest optical signal to the GW interferometer; temperature stabilization will be incorporated to simulate the LISA spacecraft will stability at the level of $10^{-3} \text{ }^\circ\text{C} / \text{Hz}^{1/2}$; a preamp input to provide 40 mW input to the amplifier to avoid instabilities caused by spurious lasing; a mechanically robust construction.

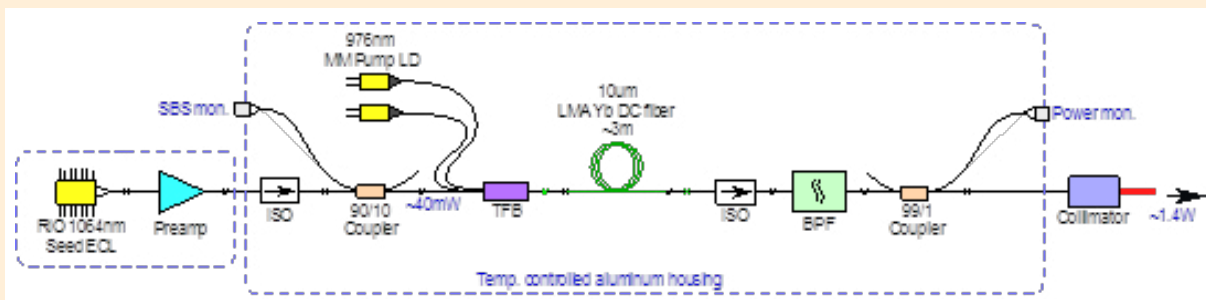


Figure 6: Laser amplifier rebuild.

4. Full Laser System Testing → TRL 5

With TRL 5 achieved for the individual oscillator and amplifier, we will next enable TRL 5 through a full system level test of the entire laser system, including power, frequency, intensity, and differential phase noise measurements. The system test uses the fully fiber-coupled setup shown in Fig. 7 and presents the amplifier, preamp, phase modulator and amplifier as one integrated system. It proceeds as follows.

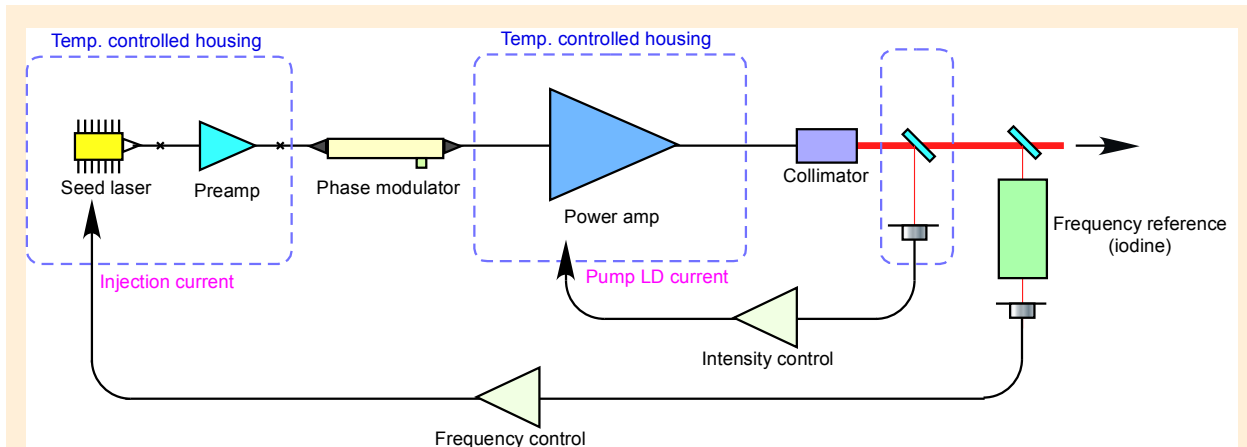


Figure 7: Systems-level test of GW laser system.

Frequency stability: A fraction of the output of the fiber amplifier will be compared to a molecular iodine frequency reference (which reaches the eLISA frequency noise requirement of $\sim 100\text{Hz}/\text{Hz}^{1/2}$ around 10 mHz.) In-band noise and long-term drift of the frequency will be monitored.

Intensity stability: Another fraction of the output will be used to demonstrate intensity stabilization. The requirements are $10^{-4}/\text{Hz}^{1/2}$ at 10 mHz, and $\sim 10^{-8}/\text{Hz}^{1/2}$ (shot-noise limit) above 1 MHz, at a detected power of 1 mW. Temperature stabilization of the detectors is also expected to address the excess intensity noise. The test will also search for any excess SBS noise that may occur in this configuration.

Differential phase noise: By using the phase modulator to apply 2 GHz sidebands to the oscillator light, the differential phase noise of the full laser system will be measured, and brought below the eLISA requirement of 10^{-3} cycle/ $\text{Hz}^{1/2}$ at 10^{-3} Hz. The relationship between the input laser frequency stability and the differential phase noise level, which may be coupled by SBS, will also be investigated.

Coupling of output power to ASE and SBS: The highest output power of the amplifier consistent with the eLISA noise requirements will be investigated. It is likely that excess noise originating from SBS and/or Amplified Spontaneous Emission (ASE) is around 2 W. This threshold will be studied in detail so that a tradeoff can be established between the eLISA shot-noise limited sensitivity and the amplifier noise and lifetime.

Long-term monitoring and accelerated aging: All aspects of the laser system performance at an elevated power level around 2 W will be monitored, while also operating the laser at an elevated temperature, around 50°C , with the laser placed in a temperature controlled chamber

at Goddard. This study will take place for 6 months and will be an accelerated test of the required 2-year laser lifetime.

Thermal cycling: The final test of the laser system will involve thermal cycling in a vacuum thermal chamber, followed by a repeat of the power and noise measurements.

Schedule

YEAR 1: Optimize the ECL design, perform the final noise testing, and finally perform the reliability testing to enable TRL 5 for the oscillator. Estimate 6 months total for: vacuum thermal cycling (2 months), hermiticity tests (1 month), radiation tests (1 month), and accelerated aging tests (4 months). Rebuild the amplifier as described above and then perform vacuum thermal cycling tests on the amplifier at the full eLISA levels. This will establish TRL 5 for the amplifier.

YEAR 2: In the second year, build a temperature stabilized enclosure and proceed with the system level test, and reach the required eLISA level of the full stabilized oscillator/amplifier system for frequency, intensity, and differential phase noise. Determine the highest power consistent with the full noise requirements, paying particular attention to the appearance of excess SBS noise. Finally, implement the 6 month accelerated aging test which will demonstrate the required 2-year lifetime, and conclude with a final check of thermal cycling of the laser. This full systems testing will establish TRL 5 for the laser system.

Task ID	Description	FY14												FY15											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	Oscillator Noise Measurements																								
2	Oscillator Reliability Tests																								
3	Rebuild of Laser Amplifier																								
4	Test Full Laser System																								

Figure 8: Laser Technology Development Schedule.

Budget

Table 3—Laser Subsystem Task Table

Task ID	Task Description	Duration (mo)	Deliverables	Dependencies	Resources		TRL	
					FTEs	Procurement (\$k)	In	Out
1.0	Oscillator Development				0.6	300	3	3
1.1	Oscillator design optimization	3		None				
1.2	Oscillator noise measurements	3		Complete 1.1				
			Thermal cycling, radiation, accelerated aging test reports					
2	Oscillator Reliability Test	6		Complete 1.2	0.5	400	3	4
			Test reports and tested amplifier					
3	Amplifier Development				0.7	100	4	5
3.1	Amplifier rebuild and noise measurements	6						
3.2	Amplifier vibration and thermal cycling	3		Complete 3.1				
			Laser system test report					
4	Test of Full Laser System				0.9	180	4	5
4.1	Construct temperature stabilized enclosure and perform system noise tests	6		Complete 2.0, 3.2				
4.2	Maximum power and accelerated aging tests	6		Complete 4.1				

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4. K. Numata et al., “Performance of planar-waveguide external cavity laser for precision measurements”, Optics Express 18 22781 (2010)
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2.3 Phase Measurement Subsystem

Function in Flight

The Phase Measurement Subsystem (PMS) is responsible for extracting the phase information from the optical beams. All LISA-like gravitational-wave mission concepts require a PMS with similar requirements: to measure interferometer signals at picometer level displacements in a low-signal visibility, high laser-frequency-noise regime.

The three laser interferometer signals the PMS will measure are:

- 1) Between spacecraft separated by millions of kilometers.
- 2) Between the lasers on the same spacecraft after reflection off the proof mass (through the aft-fiber link).
- 3) Between the local lasers through the aft-fiber link.

These signals are required by the LISA architecture at a low-speed (3.33 Hz) for the science measurement, which is sent to the ground, as well as a high-speed (>100 kHz) real-time output for laser phase-locking, wavefront sensing, and arm-locking.

In addition to tight measurement requirements (detailed in Table 2), the PMS is required to perform:

- Wave-front sensing
- Laser phase locking
- Arm locking
- Extract the phase of the clock noise tones,
- Measure the absolute inter-spacecraft ranging optical ranging, and
- Perform inter-spacecraft communications.

The phasemeter supports approximately 76 tracking channels per spacecraft.

Baseline architecture

The PMS has three main types of, photoreceivers, signal conditioning electronics, and phasemeters. The photoreceiver converts the optical intensity of the beam to a photocurrent and subsequently a voltage. A quadrant photodiode (QPD) is used to allow alignment information to be extracted. The sum of all four quadrants provides the longitudinal information from which the primary science observable is derived. A functional block diagram of the PMS can be found in Figure 1; a complete description of the PMS reference architecture can be found in Reference [1].

The phasemeter measures the phase of the signals received from the photoreceiver with respect to an ultra-stable oscillator. High-speed, simultaneously sampling ADC's digitize the signals from the quadrants of the photoreceiver after adequate filtering by analog anti-aliasing filters.

These signals are processed digitally to extract the phase information as shown in Figure 2.

The architecture of the phase measurement subsystem will be identical for NASA-led and ESA-led missions.

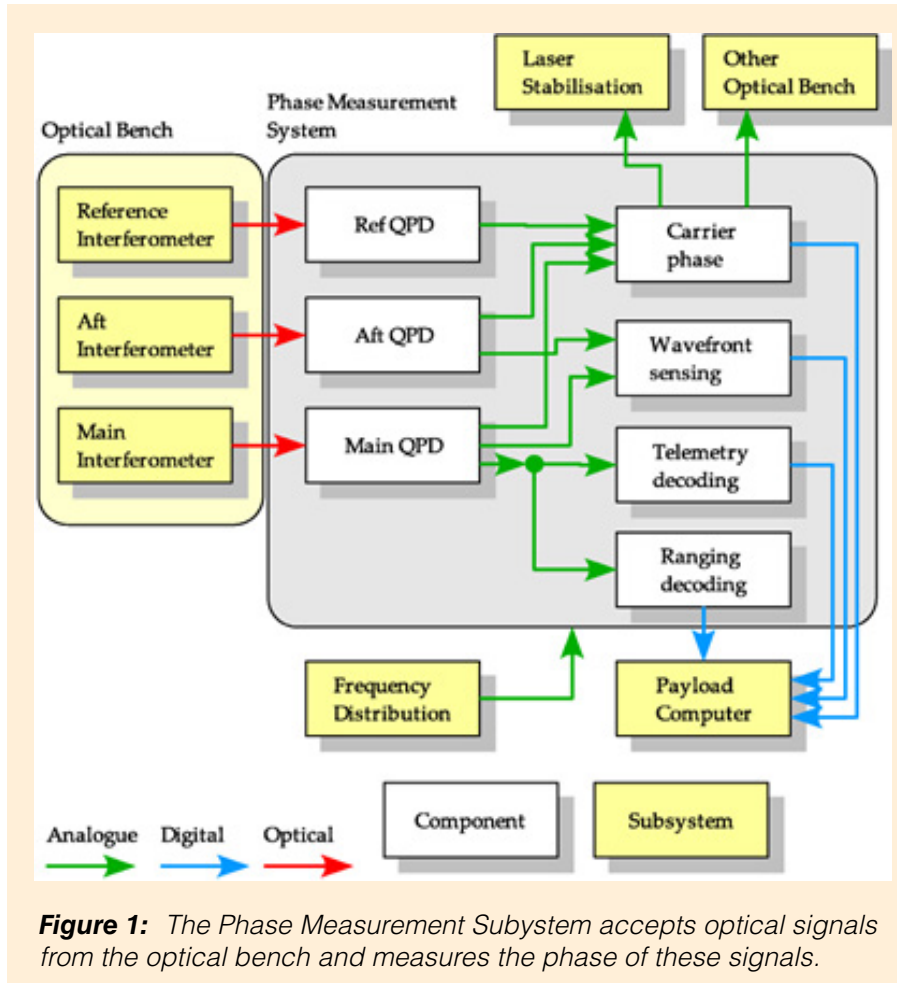


Figure 1: The Phase Measurement Subsystem accepts optical signals from the optical bench and measures the phase of these signals.

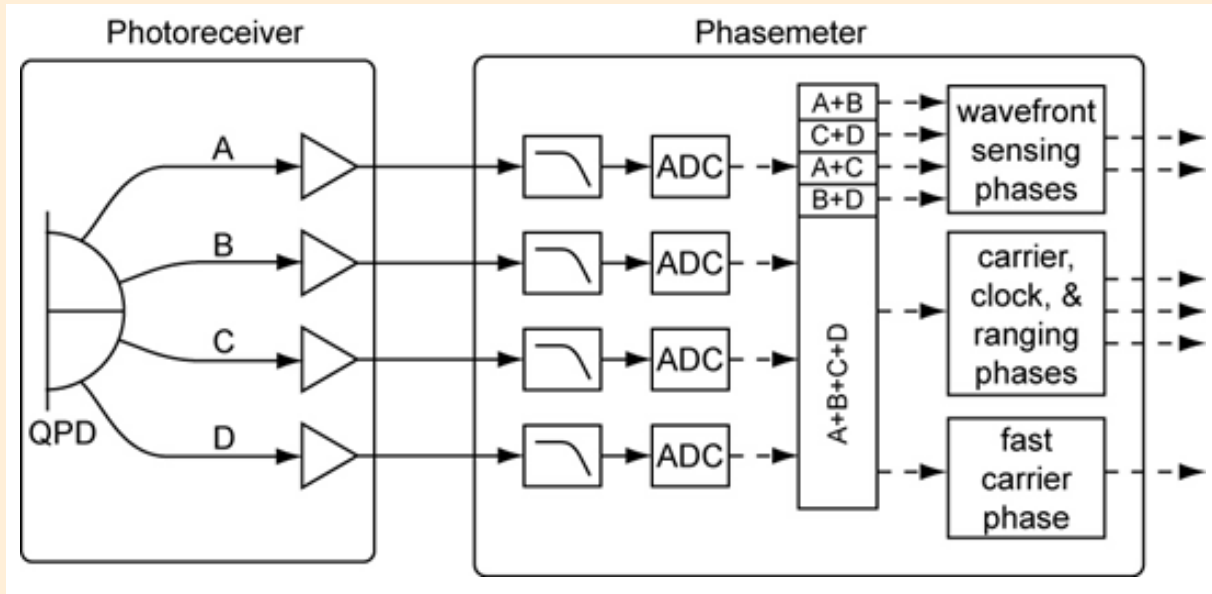


Figure 2: This image shows the architecture of the Phase Measurement Subsystem.

The Phase Measurement Subsystem for NASA-led and ESA-led missions

The phase measurement subsystem required for both mission scenarios are fundamentally the same and no change in critical requirements from the LISA baseline are necessary. Thus, we recommend PMS technology development retain the functional and critical requirements from LISA Technology Development Plan 2005 [2].

In terms of functionality for the two missions scenarios, the requirements are identical: both missions require the same basic metrology measurements of inter-spacecraft phase measurements; back-link measurements; and proof mass metrology. Both missions also require wave-front sensing, clock noise correction and optical ranging.

Minor relaxation of the critical requirements for the PMS could be found depending on mission design. For example, the frequency range of the PMS (driven by Doppler shifts of the light) carried by LISA are +/- 20 MHz. In the eLISA concept the Doppler shifts are +/- 12 MHz [11] whilst SGO-mid are +/- 2 MHz [12].

The largest difference in the PMS between the two mission scenarios is the reduction in the phase measurement channel number on the daughter spacecraft for a two-arm detector (eLISA) compared to a three-arm detector. On the daughter spacecraft there is only one proof-mass, no back-link, and only one inter-spacecraft link. This reduces the channel count number by approximately half: from 64 to 32 (TBC). However, in terms of technology development, this channel reduction on the daughter spacecraft doesn't yield a relaxation of requirements, as the mother spacecraft in the eLISA configuration still requires the same channel count as the three-arm LISA-like detector.

Risks and Requirements

Driving Requirements

The critical requirements of the photoreceiver are summarized in Table 1. Each requirement has been met by the TRL 4/5 photoreceiver.

Table 1—Critical Requirements for Photoreceiver

Photoreceiver Parameter	Derived From	Requirement
Frequency range	Functional requirements – Orbits	0.1 – 20 MHz
Phase stability	Laser/Clock/Phasemeter	$<10^{-6}$ cycles/ $\sqrt{\text{Hz}}$
Noise equivalent power	Laser/Clock/Phasemeter	$<10^{-11}$ W/ $\sqrt{\text{Hz}}$
Saturation power	Laser/Clock/Phasemeter	>5 mW
Photodiode responsivity	Shot Noise	>0.6 A/W
Number/type of elements	Functional requirement	4 quadrants

The critical requirements of the phasemeter are summarized in Table 2. The signal frequency range requirement is set by the maximum Doppler shift experienced by the light. Optimization of the orbits to minimize relative sciencecraft velocity may lead to a slight reduction in the upper limit of the frequency range. This Doppler shift drives requirements for both the photoreceiver, phasemeter, and frequency distribution subsystems.

Table 2—Critical Requirements for Phasemeter

Phasemeter Parameter	Derived From	Requirement
Dynamic range	Laser/Clock/Phasemeter	$>1.6 \times 10^6/f$
Phase sensitivity	Laser/Clock/Phasemeter	<5 $\mu\text{cycles}/\sqrt{\text{Hz}}$
Signal frequency range	Functional requirements—Orbits	0.1 – 20 MHz
Phase meter tracking (fringe rate)	Functional requirements—Orbits	>4 Hz/s
Number of tones (main interferometer)	Functional requirements	5
Ranging tone phase accuracy	Laser/Clock/Phasemeter	<5 μcycles

Risks

Development and validation of the phase measurement subsystem has addressed the majority of the critical requirements. To date, there are two notable deficiencies in the validation:

- **Wavefront sensing has not been implemented.**

Until recently, the TRL 4 phasemeter did not have the ability to read out the large number of signal channels representative of LISA-like missions, including those coming from wavefront sensing which quadruples the number of tracked channels compared to single-element detectors. Wavefront sensing has different requirements to laser frequency control and length sensing because the measurement of the *absolute phase difference* between photoreceiver quadrants is required. This couples low frequency noise in uniquely and needs to be verified.

- **Representative low-optical power signals have not been used.**

By design, the testbed was implemented with larger optical signals than expected for a gravitational wave mission. Work to date has been aimed to address higher-risk elements of phase tracking related to laser frequency noise, and the use of LISA levels of (low) optical power has not been used. Low light power levels phaselocking has been demonstrated with the TRL-4 phasemeter in recent work. However, displacement performance, TDI, and optical ranging have not been shown at with low optical power.

- Improved Testbed Fidelity. Previous testbed demonstrations have been performed approximately the $40\text{pm}/\text{rtHz} \times \text{NSF}$, representing the total interferometry displacement budget. Here NSF is the Noise shape Function given by $[\sqrt{1+(3\text{mHz}/f)^4}]$. The goal for the PMS, without shot noise levels is $13\text{pm}/\text{rtHz} \times \text{NSF}$.

The first two elements are crucial capabilities to LISA-like missions and can be retired in an effort that will culminate with an end-to-end test that will raise the entire PMS to TRL 5.

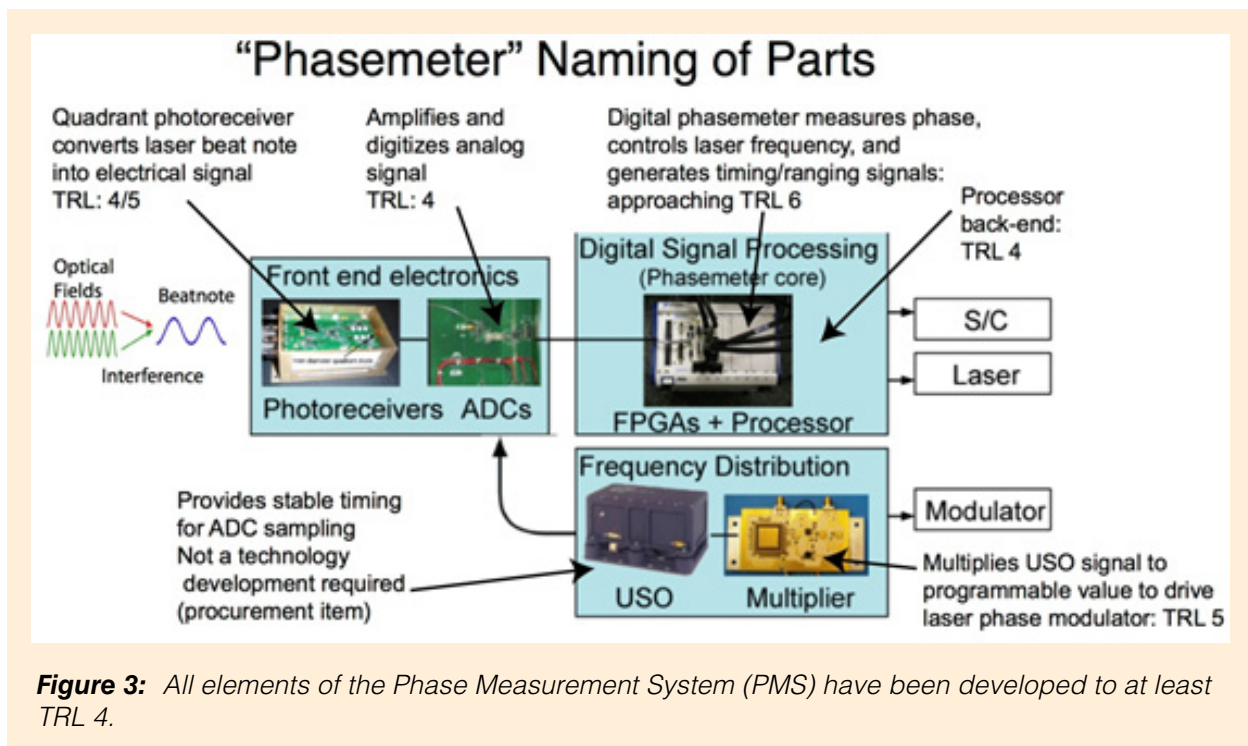
Previous Work and Current Assessment

Technology Readiness Levels

The Technology Readiness Levels for components of the PMS are shown in Figure 4 and Table 3. NASA's technology development since 2005 has increased the TRL from approximately TRL 2 at the time of the LISA Technology Development Plan 2005 [2] to TRL 4 for the PMS and TRL 4 or beyond for all PMS components.

Table 3—Technology Readiness Levels for components of the Phase Measurement Subsystem

Component	Technology Readiness Level
Photoreceiver	4/5
Analog to Digital Converters (ADCs):	4
Digital Signal Processing (Phasemeter core)	Approaching 6
Processor Back-end	4
Frequency Distribution Multiplier	5



Phase Measurement Subsystem Advances

At the time of writing the LISA Technology Plan 2005, no photoreceiver or phasemeter existed that could meet LISA’s requirements. Since then, NASA’s investments in the PMS have significantly improved the technology readiness of all components in the PMS to TRL 4, or above (shown in Figure 3). Targeted investment in the LISA phasemeter [3] has produced design breakthroughs and technical maturity that makes it the state-of-the-art in terms of meeting all critical FPGA performance requirements and all required functionality (Table 4). The NASA developed LISA phasemeter represents a strategic asset for participation either in an ESA L-class mission or a NASA-led mission.

Table 4—The LISA phasemeter has demonstrated full functionality and performance on a limited number of signals

Phasemeter Features	Phasemeter Performance	
Multi-tone tracking	Measurement limit	0.1 $\mu\text{cycle}/\sqrt{\text{Hz}}$
FPGA FFT automatic tone acquisition	Nonlinearity	$< 10^{-14}$
Automatic gain control	Aliasing	$< 1 \mu\text{cycle}/\sqrt{\text{Hz}}$
ADC jitter removal	Amplitude sensitivity	$< 0.014 \mu\text{cycle}\%$
PRN ranging	Quantization noise	$< 0.1 \mu\text{cycle}/\sqrt{\text{Hz}}$
Optical communications	Frequency slew rate	758 KhZ/s
	Track Doppler	2–18 mhZ
	Laser phase-locking	$< 10 \mu\text{cycle}/\sqrt{\text{Hz}}$ @ 139 Pw

In addition to individual PMS component development, a specially designed LISA interferometer testbed (Figure 4 and references [4, 5]) was developed at JPL to test PMS components in a representative environment. This interferometry testbed has the crucial characteristics of a space-born distributed interferometer as conceived in all interferometer-based gravitational wave missions, including: polarization leakage interferometry; multiple heterodyne frequencies; independent clocks; and independent phase measurements of optical signals and clock sidebands. Multiple heterodyne frequencies are required to avoid artificial common-mode cancellation of nonlinear effects. A representative signal structure for testing these concepts is obtained with two optical benches. This has enabled TRL 4 validation of hardware as well as testing Time-Delay Interferometry [4], and optical-ranging and optical communications [6]. Components of LISA interferometry and LISA interferometry link functional requirements have also been performed in other interferometry testbeds e.g., [7, 8].

Assessment of Key Milestones and Gates from LISA Technology Plan 2005

Referring to the LISA Technology Plan 2005, progress against the PMS milestones can be assessed.

Table 5—2005 LISA Technology Plan Milestones for the PMS and Current Status

Milestone Description	Reference	Description	Status
Phasemeter (TRL 4)	[ISM-3]	Demonstrate a phasemeter meeting LISA interferometry functional	Milestone met
Photoreceiver (TRL 4)	[ISM-4]	Demonstrate a quadrant photoreceiver meeting the following requirements shown in Table 2.	Milestone met
Select Candidate Hardware and Software for Phase Measurement Subsystem (TRL 5)	[ISM-16]	Baseline processor and operating system for phase measurement system (TRL5).	Milestone met
Photoreceiver (TRL 5)	[ISM-17]	Build and test a TRL5 photoreceiver.	TRL 4/5 photoreceiver developed. Plans to reach TRL 5.
Analog-to-Digital Converter for Phase Measurement Subsystem (TRL 5)	[ISM-18]	Build and test a TRL5 analog-to-digital converter for phasemeter.	TRL 4 ADC built and tested.
Phase Measurement Subsystem (TRL 5)	[ISM-19]	Implement primary functions of the phase measurement system at TRL5 using a candidate flight processor and operating system.	PMS built and tested in interferometry testbed at TRL 4. Some PMS components at TRL4+.

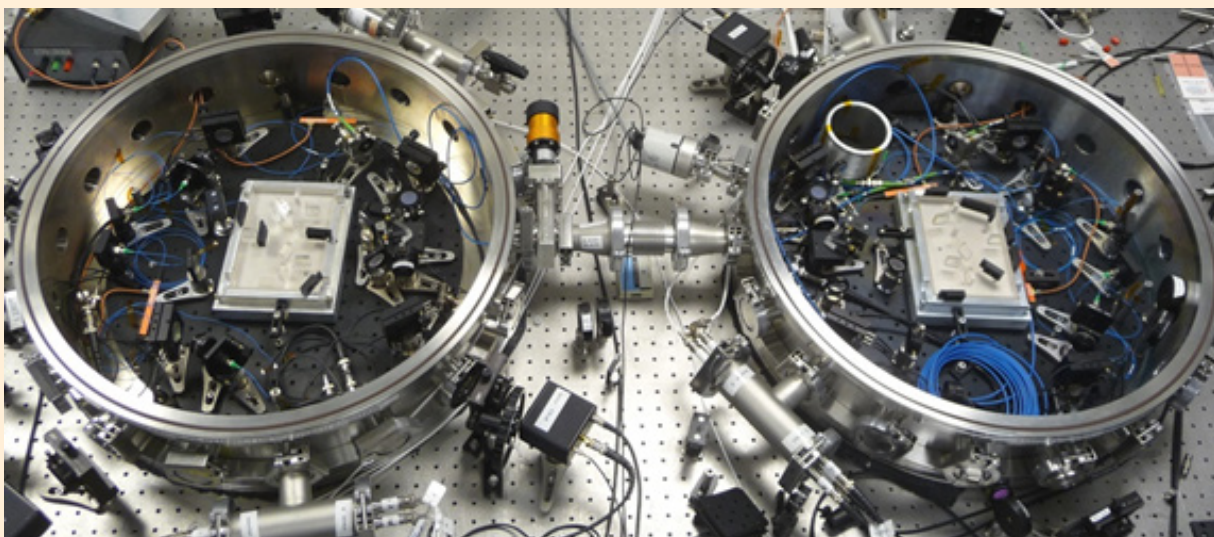
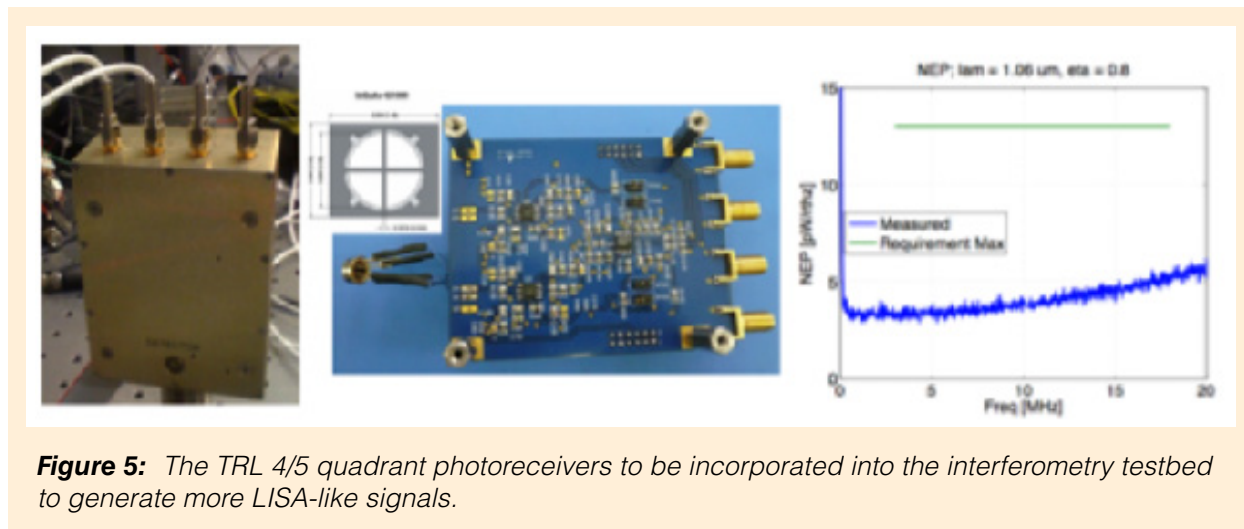


Figure 4: The LISA interferometry testbed delivers representative interferometry signals for Time-Delay Interferometry and is ideal for testing PMS hardware.

Phase Measurement Subsystem Components Status

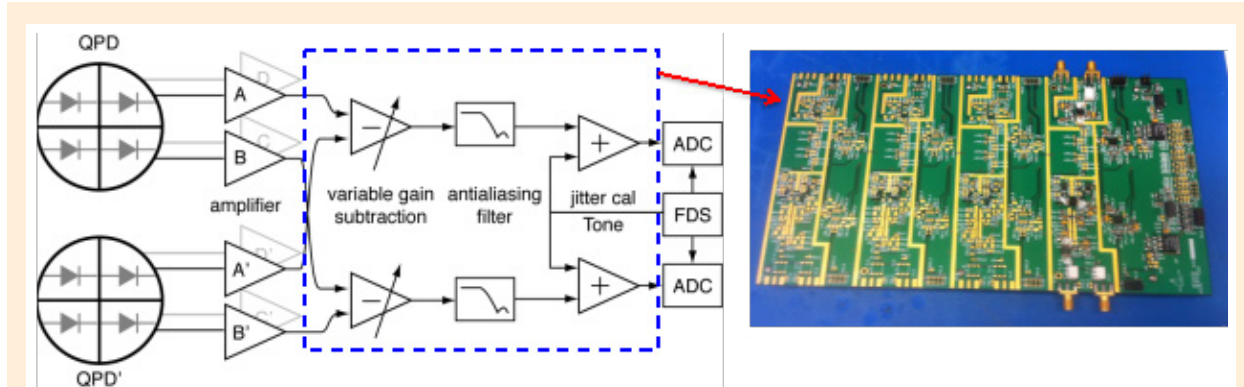
Photoreceiver

Three design variations of a photoreceiver are planned for LISA: a quadrant, low noise design for use with the interspacecraft interferometry (driving case), a quadrant design for use with the proof mass metrology, and a single-element unit for the inter-bench “back link” readout. Figure 5 shows TRL 4/5 quadrant photodetectors demonstrated to meet LISA’s demanding requirements. To accommodate the low visibility of the interspacecraft links the AC and DC signals for each quadrant follow separate amplification stages in the circuitry. Six quadrant photoreceivers have been built and tested in isolation. These units have been shown to meet the critical performance requirements; however due to a phasemeter channel limitation of a COTS TRL 4 phasemeter, these detectors have not yet been incorporated into the LISA interferometry testbed.



Analog signal conditioning chain

The AC signal from the photoreceivers passes to an analog signal conditioning board that subtracts complementary quadrants from a pair of detectors and provides anti-aliasing, as shown in Figure 6 (left). Figure 6 (right) shows a prototype analog conditioning board capable of supporting a pair of quadrant detectors. This unit has been tested to TRL 4.



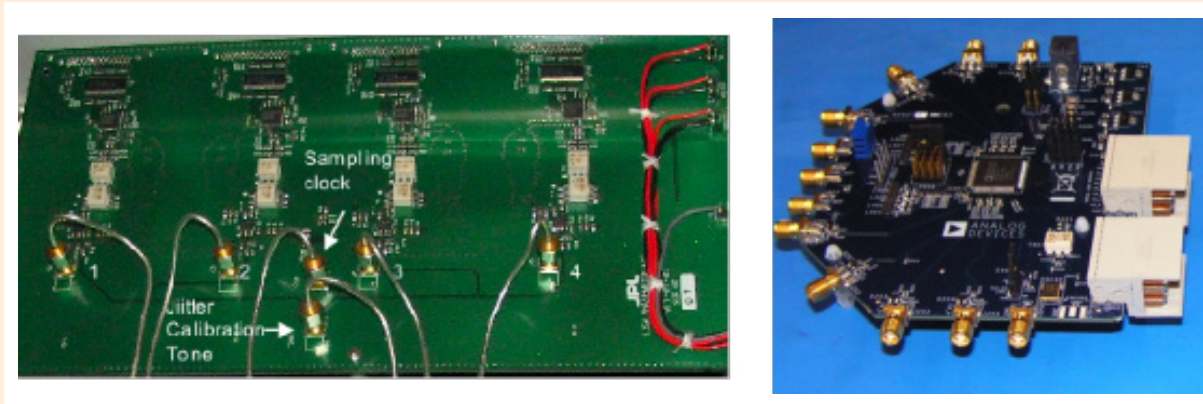


Figure 7: Several candidate analog-to-digital converters have been evaluated and meet requirements.

The large channel count makes the total ADC power dissipation a potential driving requirement for the PMS. As described above, analog signals are combined prior to digitizing, which reduces the number of ADCs required. The performance of several different ADCs, including single-channel and up to 8-channel chips (see Figure 7), has been analyzed using both TRL 4 and TRL 6 phasemeters, although not yet incorporated into the interferometry testbed.

Digital Signal Processing (Phasemeter Core)

The digital signal processing in the FPGA forms the heart of the phasemeter. It was seen as one of the most challenging components of the PMS in 2005, but now has the most advanced TRL of any component in the PMS. The digital phase locked loop (DPLL) architecture of the phasemeter is shown in Figure 8, along with the results of the “three-noise-test,” (Figure 9), which demonstrates that it meets the stringent anti-aliasing and measurement accuracy requirements to achieve large frequency noise suppression using Time Delay Interferometry (TDI). The digital signal processing represents the most critical functions of the phasemeter. The design of the digital board (Figure 10) has been raised to TRL 6.

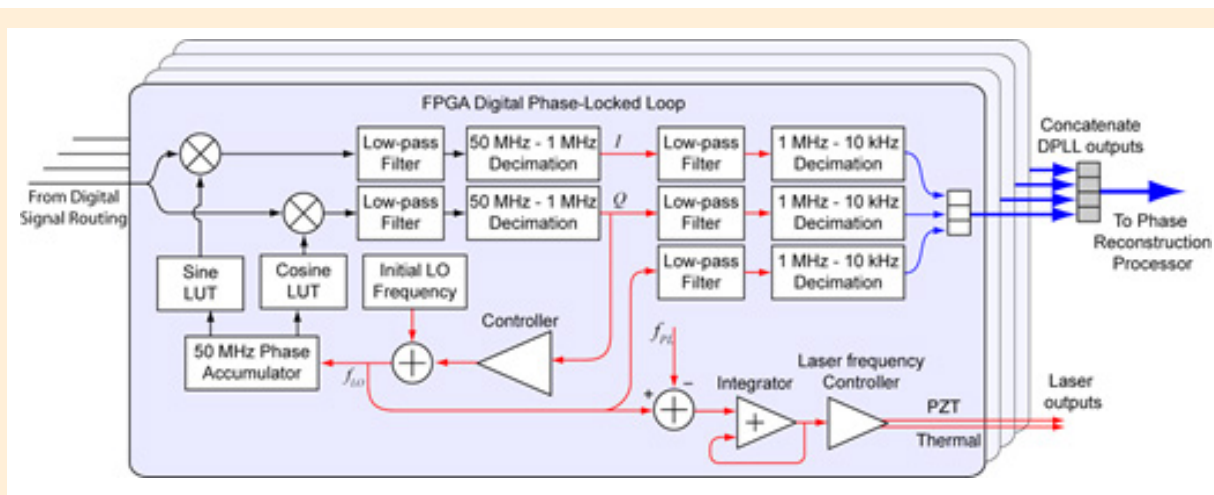


Figure 8: Block diagram of the FPGA phasemeter.

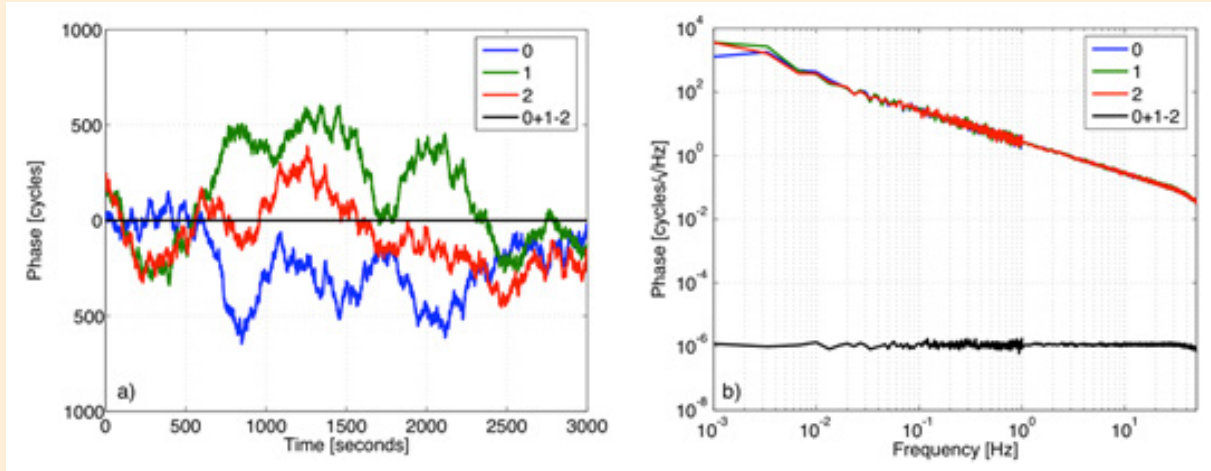


Figure 9: Time series (LHS) and RPSD (RHS) of phase measurement from three simulated correlated lasers testing the digital portion of the phasemeter. Laser frequency noise is cancelled by up to 10^9 when the three signals are combined appropriately.

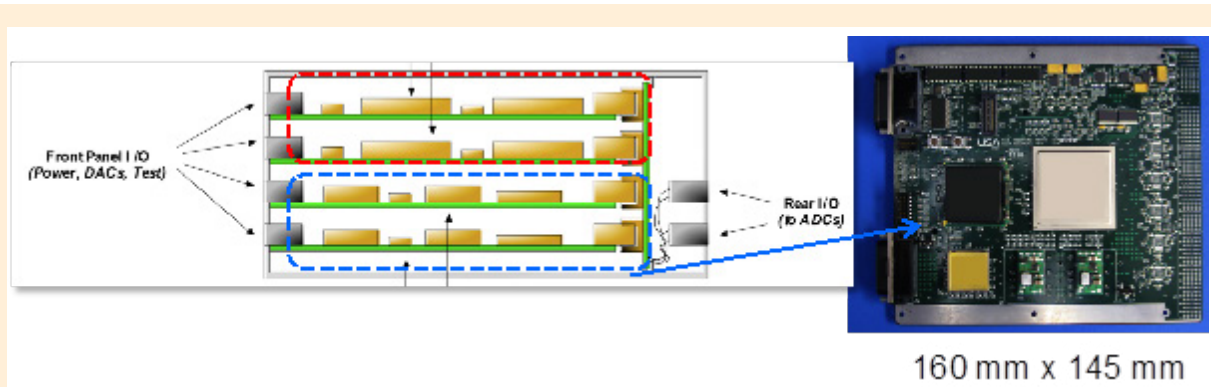


Figure 10: The TRL 6 digital phasemeter board supports the large number of analog signal channels.

Technology Development Goals

The goals of the PMS technology developments are to: (A) increase the TRL of the PMS from TRL 4 to TRL 5, and (B) retire outstanding PMS risks. The summary of current TRL and proposed TRL advancements are shown in Table 6.

Technology development required to advance the TRL of the entire PMS from TRL 4 to TRL 5 has two parts: 1) individual components upgraded, and 2) demonstration in an upgraded interferometer-system level testbed.

The outstanding (untested) PMS risks are: wavefront sensing, low optical power (LISA-like) signals, and demonstration of TDI at the LISA displacement noise allocation.

Table 6—Advancing the PMS TRL from 4 to 5 and advancing component TRLs

Item	Starting TRL	Exit TRL	Comment
PMS	3/4	5	Based on testing with advanced component prototypes in a higher fidelity signal environment
Photoreceiver	4/5	5	Successful custom chip would be TRL 6, but expected to require iteration
Signal Conditioning	3/4	5	
Digital Phasemeter	6	6	
<i>Frequency Multiplier</i>	> 6		<i>GRAIL heritage</i>
<i>USO</i>	> 6		<i>Flight procurement</i>

Increasing the Technology Readiness Level of the PMS

Continuing the development of the PMS and increasing the fidelity of the LISA interferometry testbed will provide the most mature PMS demonstration for a LISA-like interferometer to date.

1) PMS component upgrade

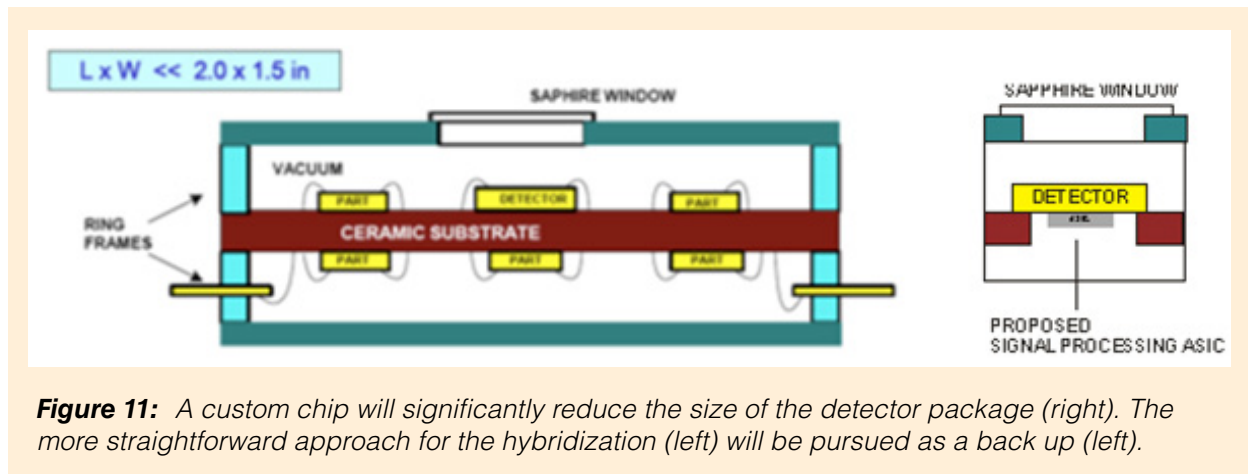


Figure 11: A custom chip will significantly reduce the size of the detector package (right). The more straightforward approach for the hybridization (left) will be pursued as a back up (left).

Two PMS components require upgrading for the system to reach TRL 5:

- **Signal Conditioning Board and Analog-to-Digital Converter:** While the performance of several different ADCs has been evaluated, the ADC design is immature. To increase the TRL, the path is to design a second-generation signal conditioning board for use in the current testbed as it is; before creating a board implementing ADC interfaces for use with the TRL 6 digital phasemeter board. This second board will advance the TRL of signal conditioning board to TRL 5.

- **Photoreceiver:** To progress the photoreceiver design to TRL 5, the architecture of the TRL-4 Photoreceiver will be migrated to parts compatible with the space environment, which will start with a radiation analysis of the critical first op-amp in the transimpedance circuit. To minimize the size and develop suitable packaging compatible with integration onto a spacecraft-based optical bench there are two paths as shown in Figure 11. Left: hybridization, which offers a low risk development approach based on conversations with vendors and the past experience; and Right: integration onto a custom chip, which offers a more substantial reward. These approaches could be followed in parallel and will be tested both for wavefront sensing performance and for the primary interferometry at the system level to TRL 5 by the completion of this effort.

2) Interferometry-Testbed Demonstration with High TRL Components

The following PMS components will be incorporated into the interferometry-testbed to increase the TRL of the PMS. A schematic of this task is shown in Figure 12.

- **Quadrant Photoreceivers:** The recently developed TRL 4 quadrant photoreceivers will replace the COTS single element photoreceivers in the testbed. This will enable wavefront sensing to be employed and debugged whilst TRL-5 photoreceivers are developed. When TRL 5 quadrant photoreceivers are constructed they will replace the TRL 4 photoreceivers.
- **Signal Conditioning and Analog-to-Digital Converters:** The signal conditioning electronics and ADCs developed under this technology plan will be incorporated into the interferometry testbed, providing an interface for the quadrant photoreceivers to the TRL-6 digital phasemeter.
- **Phasemeter Digital Board:** The TRL-6 phasemeter board is has the highest maturity of the components in the PMS, but is yet to be tested along side of the corresponding prototype components in the interferometry-testbed.

This end-to-end test provides testing and integration at a fidelity that cannot otherwise be replicated. The value will be in both interfacing hardware and conceptual insight that arises when performance testing in a relevant signal environment.

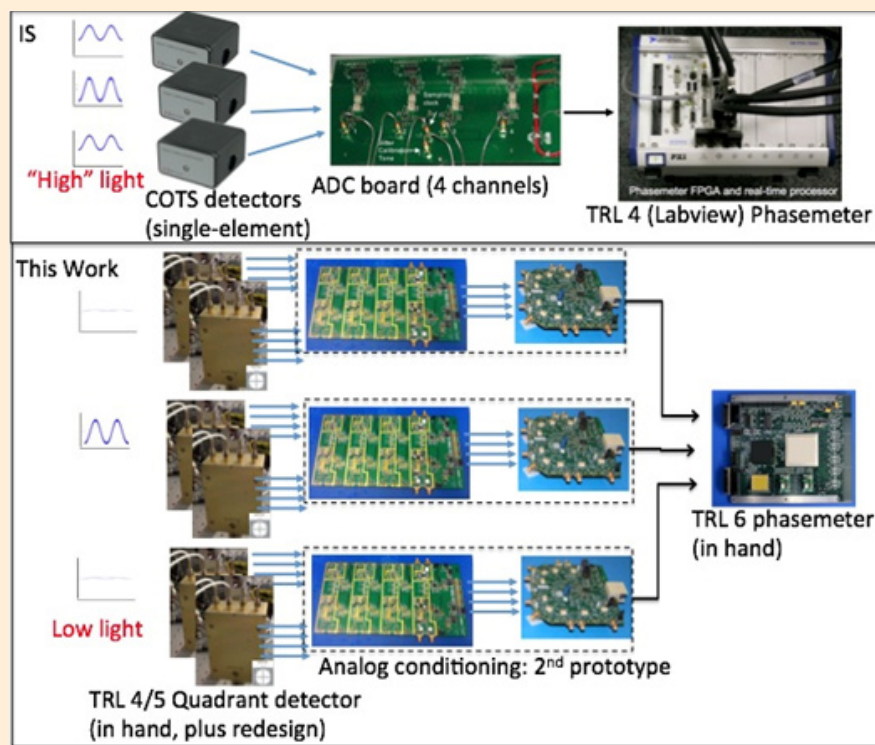


Figure 12: End-to-end testing of component prototypes into the Interferometry-Testbed raising it from TRL 4 to TRL 5.

Milestones and Schedules

Because of previous investment and development of individual PMS components and the interferometry testbed, TRL-5 system-level maturity can be realized in a relatively short time and correspondingly low cost. Proposed milestones and schedules are shown in Table 7 and Figure 13, assuming a 2-year development phase. Key milestones include:

- 1) Incorporate three existing quadrant photoreceivers into one “spacecraft” of the interferometry-testbed, reproduce testbed performance and noise suppression and single-element commercial photodiodes and TRL4 phasemeter on the other.
- 2) Implement a low visibility signal more representative of expected signal environment in LISA-like missions.
- 3) Design, build and test a second generation analog signal chain for use with a “spacecraft” worth of quadrant detectors (TRL-4 version).
- 4) Complete design study for photoreceiver custom integrated circuit design.
- 5) Down-select photoreceiver packaging path.
- 6) Design and fabricate TRL-5 signal conditioning board, including ADC/sampler
- 7) Incorporate TRL-6 phasemeter board with large number of quadrant signals and test in upgraded testbed (raises Phase Measurement System from TRL 4 to TRL 5).

Table 7—Proposed 2-year Development Schedule

Task ID	Task Description	Duration (mo)	Deliverables	Dependencies	Resources		TRL	
					FTEs	Procurement (\$k)	In	Out
1	Quadrant Photoreceiver and Custom ADC Development	18	TRL 5 analog signal chain		0.95	85	4	5
1.1	Design second generation analog signal chain	3			0.2			
1.2	Build second generation analog signal chain	1.5	TRL 4 analog signal chain	Complete 1.1	0.15	10		
1.3	Design study of photoreceiver	6			0.2			
1.4	Downselect photoreceiver TRL 5 path	0.25			0.05			
1.5	Design TRL 5 signal conditioning board, including ADC/sampler	4			0.25			
1.6	Fabricate TRL 5 signal conditioning board, including ADC/sampler	3	TRL 5 analog signal chain			75		
2	Interferometry testbed experiments	24	TRL 5+ demonstration of PMS		1.3	15	4	5
2.1	Incorporate existing quadrant photoreceivers into interferometry testbed	5			0.35			
2.2	Implement low-visibility signals into testbed	3	LISA representative signals in testbed		0.3			
2.3	Incorporate TRL 5 signal conditioning board into testbed	4		Complete 1.6, 2.2	0.1			
2.4	Incorporate TRL 6 phasemeter board with		Laser system test report					
2.5	Maximum power and accelerated aging tests	6		Complete 4.1				

Task ID	Description	FY14									FY15									FY16															
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1	Quadrant Photoreceiver & Custom ADC Development	[Gantt bar from Oct FY14 to Sep FY15]																																	
1.1	Design 2nd Generation Analog Signal Chain	[Gantt bar from Oct FY14 to Dec FY14]																																	
1.2	Build Second Generation Analog Signal Chain	[Gantt bar from Dec FY14 to Jan FY15]																																	
1.3	Design Study of Photoreceiver	[Gantt bar from Feb FY15 to Jul FY15]																																	
1.4	Downselect Photoreceiver TRL5 Path	[Gantt bar from Jul FY15 to Jul FY15]																																	
1.5	Design TRL5 Signal Conditioning Board, including ADC/Sampler	[Gantt bar from Aug FY15 to Dec FY15]																																	
1.6	Fabricate TRL5 Signal Conditioning Board,	[Gantt bar from Feb FY16 to Apr FY16]																																	
2	Interferometry Test Bed Experiments	[Gantt bar from Oct FY14 to Sep FY16]																																	
2.1	Incorporate existing Quadrant Photoreceivers into Interferometry	[Gantt bar from Oct FY14 to Mar FY15]																																	
2.2	Implement Low Visibility Signals into Testbed	[Gantt bar from Oct FY14 to Dec FY14]																																	
2.3	Incorporate TRL5 Signal Conditioning Board into Testbed	[Gantt bar from Apr FY16 to Jul FY16]																																	
2.4	Incorporate TRL 6 Phasemeter Board with large number of Quadrant Signals	[Gantt bar from Feb FY15 to Jul FY15]																																	
2.5	Interferometry Test Bed Experiments with TRL 5/6 Hardware	[Gantt bar from Aug FY15 to Dec FY15]																																	

Figure 13: Phasemeter.

Budget to Reach TRL 5

Table 8—Budget to Reach TRL 5

	Year 1	Year 2	Total
Procurements	\$25k	\$75k	\$100k
FTE	1.25	1	2.25

As described above, much of the work will be upgrading the TRL-4 phase measurement chain. For this task, much of the infrastructure already exists. As a result, the chief expenses are for development and fabrication of the hybridized photoreceiver chip and for labor.

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2.4 Optical Bench Subsystem

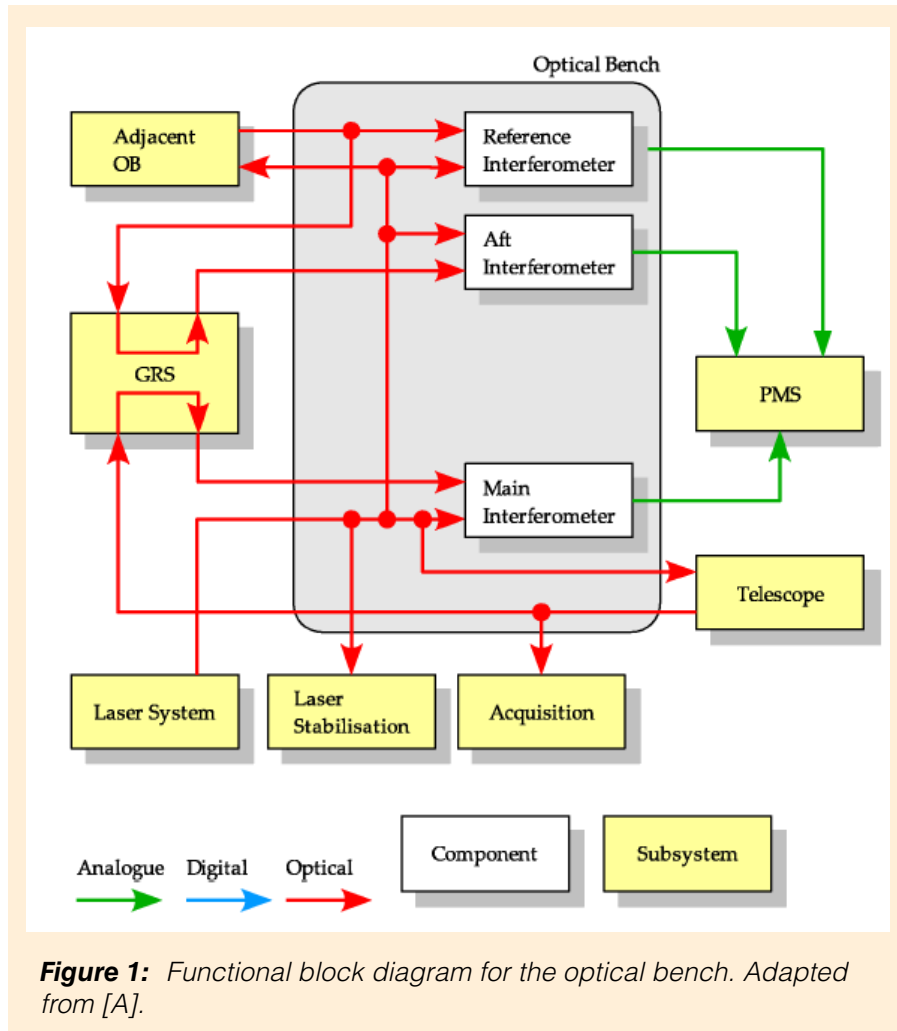
Role in Flight System

The primary function of the optical bench (OB) in a space-based LISA-like gravitational wave detector is to generate optical interference between several pairs of light beams. The phase of these interference patterns is tracked and recorded by the phase measurement system (PMS) (Section 2.3) and processed to extract information including the position and attitude of the test mass relative to the spacecraft, phase fluctuations in the long-baseline optical paths caused by passing GWs, the angle of the beam coming in from the far spacecraft, and the relative phase of the various laser master oscillators used to produce the beams. Table 1 lists the functions of the optical bench in the LISA Reference Architecture.

Table 1 – Functional Requirements of the Optical Bench Subsystem

Function	Description
OB-F1	Receive light from the telescope, interfere it with light from the reference oscillator, and place the interference pattern on the appropriate photosensitive elements of the PMS.
OB-F2	Reflect light from the local oscillator, interfere it with light from the reference oscillator, and place the interference pattern on the appropriate photosensitive elements of the PMS.
OB-F3	Send light from the local oscillator to the telescope with appropriate beam parameters.
OB-F4	Receive light from the adjacent optical bench (the reference oscillator), interfere it with the local oscillator, and place the interference pattern on the appropriate photosensitive elements of the PMS.
OB-F5	Send light from the local oscillator to the adjacent optical bench to serve as the adjacent bench's reference oscillator.
OB-F6	Provide an optical frequency reference for the local oscillator and place the appropriate optical output of the frequency reference on the appropriate photosensitive element of the laser stabilization subsystem.
OB-F7	Place light from the local oscillator on the appropriate photosensitive element of the laser stabilization system to serve as a reference measurement for laser power stabilization.
OB-F8	Provide a low-disturbance environment for performing interferometry such that the OB contributions to strain sensitivity satisfy the error budget.
OB-F9	Provide light from the telescope to the constellation acquisition system CCD.
OB-F10	Host the optical switch for selecting the primary or redundant source for the local laser system.
OB-F11	Connect rigidly to the telescope
OB-F12	Connect rigidly to the GRS

A key feature of the optical bench is the large number of interfaces with other subsystems (see Figure 1). The laser subsystem provides a light source for the OB via optical fibers. The OB is also a likely place to implement a switch for selecting the primary or redundant laser system. The OB sends and receives a beam from the test mass and must accommodate a range of test-mass positions and angles. The OB sends and receives beams to the far spacecraft via the telescope subsystem and must accommodate a range of angles. If it is required, the OB is also the likely place for a point-ahead angle (PAA) mechanism. If two OBs are used in each S/C (as in LISA), a full-duplex free-space or fiber-based optical link must be established between them. Finally, as mentioned above, the OB houses the photoreceivers for the PMS.



Baseline Architecture

The key requirement of the OB subsystem is that the optical path lengths on the bench be sufficiently stable so as not to introduce additional phase noise that would obscure the GW signals. For LISA-like mission concepts, the required stability is on the order of picometers ($1\text{pm} = 10^{-12}\text{ m}$) [A]. This path length stability is achieved in the baseline LISA architecture by constructing the bench from materials with low thermal expansion coefficients, employing ultra-stable bonding techniques, and by passive thermal isolation of the bench from the environment

to achieve $\sim 1\mu\text{K}/\text{Hz}^{1/2}$ temperature stability. The LISA baseline architecture is likely to be adopted in both the ESA-led and NASA-led implementation scenarios discussed previously (Section 1.5).

One alternative to the LISA baseline is to replace some of the stable optical paths with optical fibers, which are smaller, lighter, and do not require the same precision alignment as free-space optics. To cope with the unacceptably large phase noise that typically accompanies optical fibers, a more sophisticated metrology technique, known as digital interferometry (DI) [B], could be applied to one or more portions of the optical bench. Given the compressed timeline of the ESA-led scenario, it is unlikely that such an alternative would be incorporated. In the longer-term NASA-led scenario it is conceivable that such an option could be incorporated provided it is demonstrated to reduce cost or risk.

Risks and Requirements

There are two primary technical risks for the OB. The first is that the path length noise in one or more of the interferometers is larger than the allocated value. Such increased noise could have a direct adverse impact on the sensitivity to GWs. This risk can be mitigated by demonstrating the path-length stability at the subsystem and system level in ground tests and by including appropriate margins over CBEs when making allocations to the OB system and subsystems.

The second technical risk for the OB system is that one or more of the interferometers fail to produce any signal at some point during the mission. The baseline design does not generally include redundant interferometers. The loss of an interferometer would generally lead to the loss of a constellation link. For a two-arm constellation, this would be a mission ending failure, while for a three-arm constellation it would reduce broad-band sensitivity by a factor of $\sim\sqrt{2}$ and have a larger adverse impact in parameter estimation. Single-string interferometers are selected because it is more cost-effective to increase the reliability of each interferometer rather than incur the severe additional costs in mass, volume, and laser power that would be required for redundant interferometers. It is worth noting that the component of the interferometer with the lowest reliability, the photoreceiver, is redundant in the sense that each beam splitter is read out at both ports. Using a single port would increase exposure to straylight effects but would likely lead to a graceful degradation rather than a total failure of the interferometer.

In addition to the technical risks outlined above, the baseline architecture of the OB brings some cost and schedule risk to the mission as a result of the labor-intensive build-process. The OB subsystem for LISA Pathfinder uses largely the same architecture but is at a smaller scale in terms of number of flight units (1 versus 6), number of optical components per OB (~ 20 versus ~ 80), and number of interfaces to other subsystems. While a successful LPF would retire many of the technical risks of the OB, additional research and technology development may be needed in the areas of production and manufacture.

Table 2 lists the requirements of the optical bench. The key driving requirement is on the optical pathlength stability of the interfering beams (OB-P2). Several of the other requirements are consequences of OB-P2.

Table 2—Performance Requirements for Optical Bench Subsystem

Function	Description
OB-P1	Ensure each pair of beams is sufficiently well matched in position, angle, size, and shape to produce a good optical interference signal. This is typically characterized by the contrast, $0 < c < 1$. For LISA, the contrast targets are ~ 0.8 .
OB-P2	Limit path length fluctuations on the optical bench itself to a level sufficiently below the single-link displacement sensitivity. For LISA, the path length allocation is roughly $1 \text{ pm/Hz}^{1/2} \times \sqrt{(1+(3\text{mHz}/f)^4)}$.
OB-P3	Have sufficient mechanical strength and stability to survive launch and extended cruise while maintaining the contrast and path length requirements (i.e., exclude or minimize the need for any post-launch re-alignment mechanisms).
OB-P4	(Derived from OB-P2) Minimize the effect of scattered light to a level sufficiently below the path length allocation. This requires careful optical design and good optical coatings. The precise requirement is a combination of the amount of scattering from the surface that reaches the photoreceiver and the length stability of the scattering path (e.g., higher scattering is acceptable from more stable paths).
OB-P5	(Derived from OB-P2) Maintain temperature stability of the bench so that thermoelastic deformations do not generate unacceptably large path length noise or contrast defects. For typical ultra-low expansion materials, the derived temperature requirement for the LISA optical bench is $\sim 10\mu\text{K/Hz}^{1/2}$ at 1mHz.
OB-P6	(Derived from OB-P2 and OB-P5) Minimize power dissipation on the bench, either from absorbed light (e.g., beam dumps) or from electrical devices such as photoreceivers or active optics.

Status

The vast majority of work on OBs for GW detectors has taken place in Europe, specifically at the University of Glasgow, and has been targeted towards the needs of LPF. Milestones that have been achieved include the selection and verification of a suitable bonding technology (hydroxide catalysis bonding, or HCB) [C], development of techniques for precisely positioning optical components using HCB [D], and development of metrology techniques for characterizing the as-built OB [E]. A successful LPF flight will raise many of these underlying OB technologies to high TRL. At the time of this writing, two flight optical benches (primary and spare) have been successfully delivered by the University of Glasgow to the LPF prime contractor for integration [C]. Launch of LPF is expected in mid-2015. There are, however, a number of differences between the OB requirements for LPF and the requirements for a full-scale LISA-like GW instrument. These are listed in Table 3.

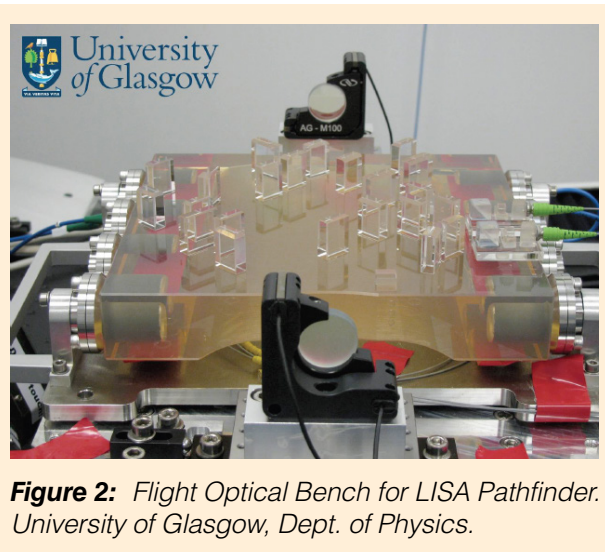


Figure 2: Flight Optical Bench for LISA Pathfinder. University of Glasgow, Dept. of Physics.

Table 3—Performance Requirements for Optical Bench Subsystem

	LISA Pathfinder	LISA/eLISA
OB Size	~20 cm square	~40 cm round
# Optical Components	~20	~80
# of Flight Units (incl. spares)	2	~10
Light Power	~10mW	~1W
Telescope Interface	No	Yes
Backlink Fiber Interface	No	Yes
Laser Redundancy Switch	No	Yes
Point-Ahead Angle Mechanism	No	Yes
Test-mass Interface	Non-normal incidence, linearly polarized	Normal incidence, circularly polarized
Photoreceiver Size	~5mm	~0.3 mm
Optical Frequency Reference	Mismatched Mach-Zehnder	Fabry-Perot Cavity

A few groups in the U.S. have some experience in OB technology. The HCB technique was originally developed at Stanford for the GP-B mission [F], and groups at University of Florida and GSFC are capable of performing basic bonding operations. At least one industrial contractor (Lockheed Martin) also offers some form of HCB services. Less expertise is available in the technologies to build complex optical systems using these bonding techniques. The GSFC group has built one small (20 cm square) bench with ~10 simple components as part of an IRAD-funded project. The digital interferometry (DI) technology has been developed at JPL and at the Australian National University with some laboratory prototypes demonstrated.

Development Tasks

The development tasks for the optical bench differ depending on the implementation scenario for the final GW mission.

Development plans for each of the two scenarios described earlier in the document (Section 1.5) are described hereafter.

Scenario A: ESA-led mission targeted for Cosmic Visions L2

It is expected that the University of Glasgow, which played a key role in developing and building the OB subsystems for LPF, will play the same role in the proposed eLISA mission for L2. As mentioned previously, one of the key challenges in moving from LPF to LISA is scaling the production to multiple units (~10 including flight spares). This is an area in which the U.S. may be able to provide expertise in both technical management and industrial manufacture should a workable partnering arrangement be available.

Secondly, it is worth reiterating that the OB subsystem interfaces with a number of other subsystems, such as the telescope, laser, and phase measurement system, that are possible options for U.S. hardware contribution to eLISA. At a minimum, the U.S. research community will need to pay close attention to the design and development of the OB in Europe. It may also be necessary to duplicate some aspects of OB technology in order to develop ground-support equipment for validation.

Scenario B: NASA-led mission targeted for Astro2020

In the NASA-led mission scenario, it will be advantageous to try and engage European partners with experience designing and building OBs for space-based GW detectors. It may even be possible to have the flight OBs provided by a European partner. However, given that the OB represents the physical core of the IMS, it is imperative that the U.S. develop institutional knowledge in OB technology if it is to assume mission leadership.

Research Activities

The proposed research activities for the U.S. are divided into three categories: OB design, component development, and technology demonstrators. For the technology demonstrators, the OB functions are divided so that each function can be developed separately without requiring all interfacing subsystems to be developed simultaneously. Some research activities are dependant on others; for example, a complete optomechanical design is required before any of the technology demonstrators can be constructed. Table 4 lists each of the proposed activities along with their duration, deliverables, dependencies, resources, and TRL advancement. Detailed descriptions of each task can be found in the text that follows.

Table 4—Summary of research tasks for Optical Bench subsystem

Task Description	Duration (mos)	Deliverables	Dependencies	Resources		TRL	
				FTEs	Procurement	In	Out
1.0 Optical Bench Design							
1.1 Optomechanical Design	9	Complete description of functional design	None	2	\$10K	N/A	N/A
1.2 Scattered Light Model	6	Assessment of scattered light impact on science measurement	Complete 1.1	1	\$10K	N/A	N/A
2.0 Component Development							
2.1 Monolithic Fiber Launchers	18	Laboratory prototype and tests	None	1	\$150K	2	4
2.2 Point-Ahead Angle Mechanism	24	Laboratory prototype and tests	None	1	\$250K	2	4
2.3 Optical Assembly Tracking Mechanism	6	Mechanism design and preliminary analysis	None	0.5	\$10K	1	2
3.0 Subsystem Technology Demonstrators							
3.1 Reference Interferometer	12	Laboratory prototype and tests	Complete 1.1	1	\$100K	3	4
3.2 Test-Mass Interferometer	36	Laboratory prototype and tests	Complete 1.1	2	\$500K	2	4
3.3 Long-Arm Interferometer	36	Laboratory prototype and tests	Complete 1.1, 2.2	4	\$1M	2	4
3.4 Back-Link Fiber	12	Laboratory prototype and tests	Complete 1.1, 2.1	1	\$100K	3	4
3.5 Digital Interferometry Bench	24	Design, laboratory prototype and tests	None	1	\$100K	2	4
3.6 Free-Space Back Link	24	Laboratory prototype and tests	Complete 1.1, 2.1	1	\$100K	3	4

Functionally, the OB can be thought of as four primary interferometers and possibly some additional special purpose interferometers for PAA metrology, telescope metrology, etc. The four primary interferometers are the readout of the proof mass position with respect to the OB (the short arm interferometer), the read out of the motion of the OB on the local spacecraft with respect to the corresponding OB on the far spacecraft (the long arm interferometer), the read out of the backlink fiber noise (performed separately on each OB and combined to cancel the common-mode fiber noise), and a reference interferometer that measures the relative frequency noise of two of the oscillators (either the local and received or the local and adjacent).

Optical Bench Design Activity

The goal of the design research area is to develop and maintain a notional OB design that meets all of the functional and interface requirements for a notional GW mission. The obvious starting point would be a review of the LISA and NGO designs developed by the University of Glasgow and Astrium. However, it is likely that there are details that will require change as well as areas of potential improvement. An example of the former is the telescope interface, which will have to evolve with the design of the telescope. An example of the latter is the potential accommodation of a laser frequency reference on the OB, a component that was not included in the most recent LISA designs.

The design would also allow study of dimensional tolerancing of individual components and component placement, informing component specifications such as photoreceiver diameters and the design of the telescope beam expander and relay optics. These tolerances could be modeled to generate some experience and to guide first-order requirements and specifications, and then the model could be validated by actual construction. An optical design would also be used to develop a stray light model including optical components, coatings, baffling, and cleanliness issues. The results of this model would feed back both to component development and to the optical bench design itself.

A substantial initial effort would be required to develop an OB design, followed by a lower-level maintenance effort to incorporate design changes driven by other subsystems. Support required for this activity would be a supervising scientist familiar with LISA interferometry, optical engineers capable of design and modeling, and possibly a mechanical engineer for basic structural/thermal analysis. Involving the University of Glasgow scientists who have built the LPF bench and developed the current LISA design in this activity would be extremely valuable.

Alternative optical bench designs incorporating fibers and DI could also be developed, likely at a lower level of fidelity (e.g., no scattered light model to start with). These would help inform the requirements on DI as well as the potential costs and benefits of such a system.

Component Technology Development

With the exception of the all-glass fiber launchers, most of the European effort in OB development for LPF is concerned with the assembly of easily-manufactured components. The full-scale optical bench will require some additional components (e.g., PAA mechanism and primary/spare laser switch) that are not included in LPF but have undergone some development. Any OB effort in the U.S. will have to determine which of these components could or should be procured and which would require technology development.

In some cases, the component technology developments represent technologies that would enable or are required for some proposed architecture change from SGO-Mid. Those components are labeled “[Alternative]” whereas the components directly related to the baseline SGO-Mid design are labeled “[Baseline]”.

Component #1: Fiber Launchers [Baseline]

One of the key accomplishments of the University of Glasgow OB development work for LPF was the development of an all-glass fiber launcher that could be bonded directly to the OB, maintaining the high dimensional stability through launch. These launchers meet most of the requirements for LISA/eLISA with the one exception being that they have not been tested at higher light power levels. It may be possible to purchase these launchers from the University of Glasgow or license the technology so that a contractor could produce them in moderate quantities. In the case that neither of these options are possible, it would be necessary to develop an alternative. This activity constitutes redevelopment of an alternative to the University of Glasgow design.

Component #2: Point-ahead angle mechanism [Baseline]

The function of this component is to accommodate the variation in the relative angle of the transmitted and received light beams caused by the motion of the constellation. This is different than the common motion that is corrected for by the in-field guiding mechanism or the optical-assembly tracking mechanism in the case of no in-field guiding. Two designs meeting LISA requirements have been developed and tested in Europe. The baseline strategy would be to procure one of these devices, consequently the priority for this activity is low.

Component #3: Optical Assembly Tracking Mechanism Design [Alternative]

The baseline LISA design uses a telescope with a narrow FOV and moved the entire optical assembly (GRS+OB+Telescope) to track the far S/C using a device known as the Optical Assembly Tracking Mechanism (OATM). Some preliminary design work and an actuator study was completed [G]. The current goal for concepts such as NGO and SGO-Mid is to use a wider FOV and a tracking-mirror located inside the telescope, an approach known as in-field guiding. While there are advantages to in-field guiding, maintaining and refining an OATM design would provide a potential alternative should the in-field guiding approach encounter problems. While not strictly an OB activity, it is carried here since it replaces a major component on the OB.

An initial low-level effort to develop a more refined design would be appropriate, followed at a later date by construction of a prototype mechanism and technology demonstrator.

Technology Demonstrators

Technology demonstrator activities are the heart of the proposed OB development program. They provide an arena in which to validate aspects of the OB design, exercise components that have been developed, and provide insight into the measurement at a system-level. Four baseline technology demonstrators are proposed to cover each of the primary functions of the optical bench, corresponding to each of the four interferometric functions of the optical bench. The plan is for each Technology demonstrator to be built separately, possibly at separate institutions. Eventually it would be desirable to build a complete “breadboard” OB with all

functions implemented simultaneously but that is considered beyond the scope of this research plan. In addition, two “alternative” technology demonstrators are described that could be used to investigate potential architecture changes to SGO Mid. Work on these testbeds would not commence until paper studies suggest that the cost, risk, or performance improvements of the alternative warrant the investigation.

Technology demonstrator #1: Reference Interferometer [Baseline]

The goal of this technology demonstrator is to perform heterodyne interferometry between two fiber-coupled optical sources and demonstrate that the pathlength noise of the OB is below required levels. This requires a very simple bench but is a good exercise for developing the basic interfaces with the laser system and phase measurement system. This testbed would also incorporate an integrated frequency reference based either on Mach-Zehnder or optical cavity technology that has already been developed.

Technology demonstrator #2: Test-mass interferometer [Baseline]

The goal of this technology demonstrator is to perform the short-arm interferometry to read out the position of the test mass along the sensitive axis as well as the two angles normal to the sensitive axis. This is accomplished by reflecting a beam off of the test mass surface and interfering it with a reference beam on a quadrant photoreceiver. The relative phases of the quadrants are used to perform differential wavefront sensing (DWS) and infer the angle of the test mass. The technology demonstrator would require an optical bench with two laser sources, a fixed reference interferometer, and a moveable target mirror standing in for the test mass, likely on a multi-axis piezo stage. The AEI in Hannover performed this sort of testing for LPF, eventually including flight units. However, there are some significant differences between the LPF and SGO-Mid designs. The LPF design uses a non-normal incidence to decouple the beams transmitted to and reflected from the test mass. This obviates the need for a more complex polarization-switched interferometer, but it introduces different geometrical errors. The SGO-Mid design utilizes a normal-incidence polarization interferometer. The phase measurement system for LPF operates at a much lower heterodyne frequency (2 kHz, as opposed to ~10 MHz), and consequently can operate with much larger-area photoreceivers. Switching to a LISA-like PMS and smaller photoreceivers will require some design changes, especially in the area of interferometer acquisition.

One important role that this technology demonstrator could play would be in system-level studies of the disturbance reduction system. The analogous LTP technology demonstrator at AEI has been used to simulate closed-loop control of the S/C and test masses with a computer standing in for the thrusters and spacecraft dynamics [H]. It has proved extremely useful to the LTP community, both for providing insight into the measurement process and for testing engineering models and flight units of components such as the laser, laser modulator, phase meter, and flight computer.

Technology demonstrator #3: Long-arm interferometer (Telescope Interface) [Baseline]

The goal of this technology demonstrator is to validate the interface between the OB and the telescope. This includes accommodating beams of various size and angles and demonstrating the separation and measurement of the strong outgoing and weak incoming beams. This technology demonstrator will require some model of the telescope, either a full telescope model with an additional component to mimic the incoming beam or some dedicated telescope hardware model. It also would require a prototype PAA mechanism, and the in-field guiding and focus mechanisms

either as components of the OB or as components of the telescope model. An optical beam geometry that uses a telescope in a double-pass configuration so that tests could be performed on a small diameter beam could help reduce instrumentation costs for optical equipment such as full-aperture interferometers (i.e., Zygos) at the start of the program, as well as require only a single copy of the telescope.

Technology Demonstrator #4: Back-link Fiber [Baseline]

The goal of this technology demonstrator is to perform full-duplex exchange of light beams between two optical benches (or two regions of the same bench) via an optical fiber and verify that the non-reciprocal fiber noise is below the required value. Several efforts in this area were conducted in this area in the past at JPL, University of Florida, and AEI Hannover with promising results, but the full requirement was not yet demonstrated [1]. Reflections back into the fiber from the free-space (air) to glass interface at the fiber launchers appears to be a limiting issue, and this problem in particular would be one of the first issues to be addressed. This could be a good project for an independent researcher. A thorough examination of the current research results should be performed before any additional laboratory work is performed.

Technology Demonstrator #5: Digital Interferometry [Alternative]

The goal of this technology demonstrator is to study a DI-enabled OB, possibly utilizing optical fibers to reduce mass, volume, and construction complexity. It would likely start with some subset of the OB functionality, such as the long-arm interferometer, and then expand to include additional functions as appropriate.

Technology Demonstrator #6: Free-space Back Link [Alternative]

An alternative to the back-link fiber would be to connect the two OBs on each S/C with a free-space link. This would avoid some of the problems with non-reciprocal phase noise encountered in previous back-link fiber experiments. Some estimate for the relative motion of the two OBs would have to be derived from a mechanical model of the S/C. This could include both “one-time” changes such as launch effects, as well as slow-drifts caused by on-orbit thermal variations or material creep. Back-link optics would then need to be designed, possibly incorporating some active optical components. The technology demonstrator would consist of two separated OBs on a mechanical structure with the free-space link between them. The entire assembly would be subjected to appropriate environmental stresses and the capability of the link to maintain a signal would be verified.

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2.5 Disturbance Reduction System

The principle measurement of any Laser Interferometer Space Antenna (LISA)-like mission is the measurement of changes in the distance between test masses which ideally are only subject to the tidal forces of gravitational waves in the 0.1 mHz to 1 Hz LISA frequency band. The interferometry measurement system (IMS) monitors changes in the distance while the Disturbance Reduction System (DRS) includes the test masses and all other technologies needed to place them in free-fall at the level of $3 \times 10^{-15} \text{ m/sec}^2/\text{Hz}^{1/2}$. The Gravitational Reference Sensor (GRS), a key component of the DRS, is described below and shown in Figure 1. The GRS contains the test mass and its electrode housing, as well as the associated electronics, vacuum system, caging (launch-lock) system, and charge management system. In addition to the GRS, the DRS also includes micronewton thrusters and control laws, which are used to fly the LISA spacecraft in formation with the test mass to eliminate the need for test mass suspension in the sensitive direction (drag-free control [A]).

Even before LISA became a project at the European Space Agency (ESA) and NASA, the DRS has been identified as the most challenging technology that needs to be addressed before any LISA-like mission can become a reality. This is the reason for the extraordinary investments in Europe in this technology. The European GRS has been developed and studied exclusively at the University of Trento, and their excellent results nearly reaching LISA sensitivity in ground testing show that the design itself is valid; and all LISA-like mission concepts in Europe and the U.S. are based on this GRS. Problems with the space qualification of the caging mechanism and of the electrode housing, both parts of the GRS, and with the European μN thrusters are responsible for the latest delays in the LISA Technology Package (LTP). Some of these issues can be traced back to the reliance on single-source vendors that have been able to produce, in some cases, high-quality engineering units but could later not reproduce the same quality in the flight units. These are not uncommon problems in long-term research projects, but they are always costly. These problems are likely to increase given the 10- to 15-year difference between the Pathfinder and the LISA launch.

With regard to GRS development, the situation in the U.S. is orders of magnitudes more desperate. NASA has virtually no access to anything even remotely performing at the required sensitivity. This represents a major programmatic risk for NASA not only for any potential NASA-led mission, but also for an ESA-led mission with NASA as a junior partner.

Our technology development plan addresses these programmatic risks. The study of the underlying physics, the engineering aspects, and the fundamental and technical limitations of the GRS will develop U.S. competency in this critical detector technology. It will develop a U.S. vendor base that significantly reduces the reliance on single foreign vendors. Improvements in position and angular sensing and in charge management will lead to relaxations in requirements in other areas, most notably in the positioning and alignment of the spacecraft. It will also allow potential mass and power savings and improve the performance beyond the current state of the art. The proposed plan herein will also address known differences between LTP and LISA-like mission requirements, such as lifetime.

2.5.1 Gravitational Reference Sensor

2.5.1.1 Functional Description

Functionally, the GRS is part of the Disturbance Reduction System (DRS). A single GRS forms one of the end points of each interferometer arm.

The main GRS function is to provide the reference surface/mirror for the inter-sciencecraft interferometer laser beams. This reference object is known as the “proof mass” (PM). The PM also functions as a reference point for the DRS, so that, as a mirror, it can be kept isolated from nongravitational accelerations.

The most critical requirements on the GRS are therefore those that concern acceleration noise on the PM. Other GRS functions generally serve to reduce the sources of noise, such as a vacuum system to minimize the residual gas pressure near the PM. Other functions provide safety features; e.g., a caging mechanism to secure the PM during launch.

2.5.1.2 Baseline Architecture

Each LISA GRS, shown in Figure 1, consists of a 1.96 kg, 73%/27% gold/platinum cubic PM inside a molybdenum housing [B]. Each PM is 46 mm on a side. The housing holds gold-coated electrodes to sense the position and orientation of the cube via capacitive sensing and to actuate it using electro-static actuation. Readout of the sensing electrodes and driving of the actuation electrodes is performed by the front end electronics (FEE).

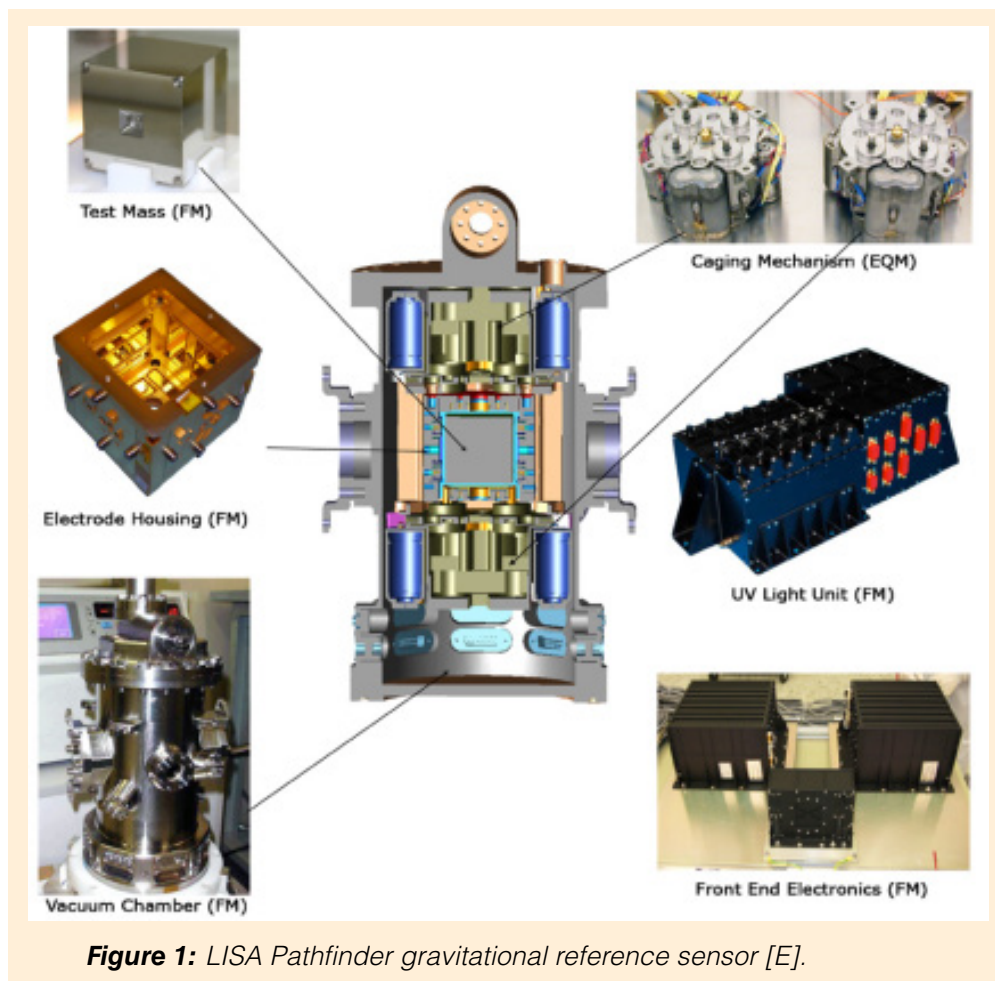


Figure 1: LISA Pathfinder gravitational reference sensor [E].

The gap between the proof mass and housing is 4 mm and is a trade-off between reducing the effects of noise sources, e.g. from uncontrolled potentials on the electrodes, and being able to meet the capacitive sensing requirement of $1.8 \text{ nm Hz}^{-1/2}$ over the measurement bandwidth. The capacitive readout system is arranged such that electrodes facing opposing faces of the PM are combined via a capacitive bridge. A change in the position of the PM gives a differential, bipolar, signal at the output of the bridge, which is used as an input to the drag-free control system. The PM and electrode housing are mounted inside a dedicated titanium vacuum enclosure.

The final sensitivity of LISA is limited by sensing noise and acceleration noise: how well can we determine the distance between the center of mass of two separated objects, and how well does each object follow its geodesic, respectively. This simplified view suggests that only the signals from the interferometric read out will be used to extract the gravitational wave (GW) signals. This is not the case. It is not expected nor planned to reduce all acceleration noise below the $3 \times 10^{-15} \text{ m/s}^2/\text{Hz}^{1/2}$ requirement. Instead, acceleration noise caused by the most prevalent sources will be estimated based on external sensors and actuators and measured and modeled transfer functions. The calibration and understanding of this low-level data are crucial for the extraction of GW signals at the required sensitivity.

2.5.1.3 Status

The LISA Pathfinder (LPF) is a technology demonstration mission of ESA scheduled for launch in 2015. LPF will test the LISA gravitational reference sensors, the drag-free control system, and ultra-precise micro-propulsion systems. Although NASA is a partner on this mission, its ST-7 contribution is limited to μN thrusters and control laws and relies on data provided by the European LTP, which includes the GRS. NASA is not involved in the development and testing of the GRS or LTP, nor does it have full access to all technical details or the data taken during the ESA-led phase of the mission. Most components have reached TRL 6 already, and the remaining ones will be matured to TRL 6 for LPF within the next 12 months in Europe. Following a successful LPF mission, differences between LPF and evolved Laser Interferometer Space Antenna (eLISA) requirements, such as lifetime, will have to be addressed.

Beyond LPF, it is not known how testing of the GRS/DRS will continue in Europe. This and the lack of knowledge in the U.S. are major programmatic risks for eLISA, and especially for a future U.S.-led mission. The University of Florida group started setting up a GRS testbed similar to the Trento testbed to develop the technology and test components in the U.S. using internal funds. However, they will not reach the required noise levels or be able to improve TRL levels unless they receive additional funding.

2.5.1.4 Risks and Requirements

The residual (un-modeled) acceleration noise of the proof mass has to be below $3 \times 10^{-15} \text{ m/sec}^2/\text{Hz}^{1/2}$ in the LISA science frequency band over the lifetime of the mission. This drives secondary requirements, including electrostatic voltage noise, thermal and magnetic stability, maximum charges and charge/discharge rates, vacuum level of the GRS housing, test mass (TM) magnetic properties, patch field stability, and TM-to-spacecraft stiffness.

The lifetime of the eLISA strawman design is 2 years with a potential 2-year extension. This is significantly longer than the 6 months of science operation for LPF, but also significantly shorter than the 5 years plus potential extensions of the original LISA mission. Lifetime is one of the major contributions NASA could provide to enhance the science potential of eLISA.

Technology risks were coordinated in 2005 by the DRS Integrated Technical Advisory Team (ITAT), which included technical representatives from ESA, NASA, and European and U.S. universities. The assessments provided in the 2005 LISA Technology Development Plan were derived from detailed consideration of the DRS performance noise budget, which flows down from mission requirements, and by functional requirements. Since 2005, a lot of work has been done to mitigate these risks, and a lot more is understood about the LISA baseline design. While a detailed update of the technology risks is not performed here, a few critical risks remain and a few new technology risks have been discovered. These include:

1. *In-band GRS electrode voltage fluctuations.* Excess electronics noise discovered in the LPF FEE will limit the acceleration noise performance for LISA. Improvements in the electronics design are needed.
2. *Caging mechanism failure during launch or during the initialization phase.* A failure of the GRS caging mechanism during LTP qualification testing has prompted a late-stage redesign, which currently drives the LPF launch schedule.
3. *Test mass charge/discharge control.* While the charge management system was designated a yellow risk item in 2005, more recent measurements using the GRS testing facility in Italy have shown that bi-polar charge control is not always robust, elevating the risk assessment of this technology. The cause is likely surface contamination on both the test mass and electrode housing causing differences in the work functions and therefore the efficiency with which electrons can be extracted from the desired surface. Improvements using higher energy (lower wavelength) ultraviolet (UV) photons from new UV light-emitting diode (LED) sources and an alternating current (AC), instead of direct current (DC), approach to charge control will almost certainly be needed for LISA.
4. *Cross-talk between TM degrees of freedom.* Test mass actuation noise and TM-to-spacecraft stiffness coupled with cross-talk between rotational and transverse displacement degrees-of-freedom will produce TM acceleration noise in the sensitive direction. Higher precision readout of non-sensitive TM degrees-of-freedom can mitigate this effect by either improving the drag-free control performance or allowing for these disturbances to be calibrated and subtracted in the data analysis.

2.5.1.5 Planned Activities

The GRS design will primarily follow that of the European LPF mission, but include several incremental improvements. These improvements will be in the areas of charge management, front end electronics, and an optical readout system for the proof mass. Five key activities will be performed:

1. The design and fabrication of a TRL 3 electrode housing with associated front end electronics.
2. The construction of a torsion pendulum facility with a light-weighted proof mass mock-up to evaluate the performance of the GRS.
3. The development of a charge management system utilizing fiber-coupled UV LEDs to control the proof mass charge.

4. The design and construction of an optical readout system to calibrate and verify the performance of the capacitive readout of the GRS.
5. Finally, execute a testing campaign to quantify key acceleration noise sources of the GRS so that they can then be modeled and subsequently minimized.

These planned activities target the identified shortcomings and risks and will lead to further improvements in the DRS and GRS in performance, mass, and power consumption. The list of components, their current status, and the TRL goals are summarized in Table 1. The target TRL for several items only requires Astrophysics Research and Analysis (APRA) funding over the next years and not Strategic Astrophysics Technology (SAT) funding; directed funding is possible at all TRL levels.

Table 1—GRS Technology Readiness Status and Goals

	TRL Now	TRL Goals	Comment
Electrode Housing	2	3 by 2017 5 by 2019	Following the LISA baseline design, but using U.S. vendors
UV-LED-based Charge Management System	2	3-4 by 2017 6 by 2020	Replace Mercury discharge lamps
Optical Readout	2	3 by 2017 5 by 2019	Improved sensing of all degrees of freedom
Front End Electronics	2	3 by 2016 5 by 2019	Improved performance, lower mass, lower power consumption

Additionally, it is highly advisable to set up a GRS testbed to develop the GRS technology in the U.S. and reduce the aforementioned programmatic risks. The test facility will also be used to test the UV-LEDs, the optical readout, and the electronics. As the GRS testbed is essential for the testing, we will describe the testbed first. This is then followed by a description of the technologies which could be tested with the GRS.

Development of a GRS test facility

The GRS testbed should consist of a four-mass torsion pendulum suspended by a fiber of at least 1 m in length. The fiber could initially be made of a high-Q metal such as tungsten, but will have to be replaced later by a higher-Q material such as fused silica or sapphire to reduce the thermal noise. The suspension point will have to be controlled by actuators to orient and position the torsion fiber correctly. The entire torsion pendulum has to be mounted in a quiet and thermally stable environment inside a vacuum chamber.

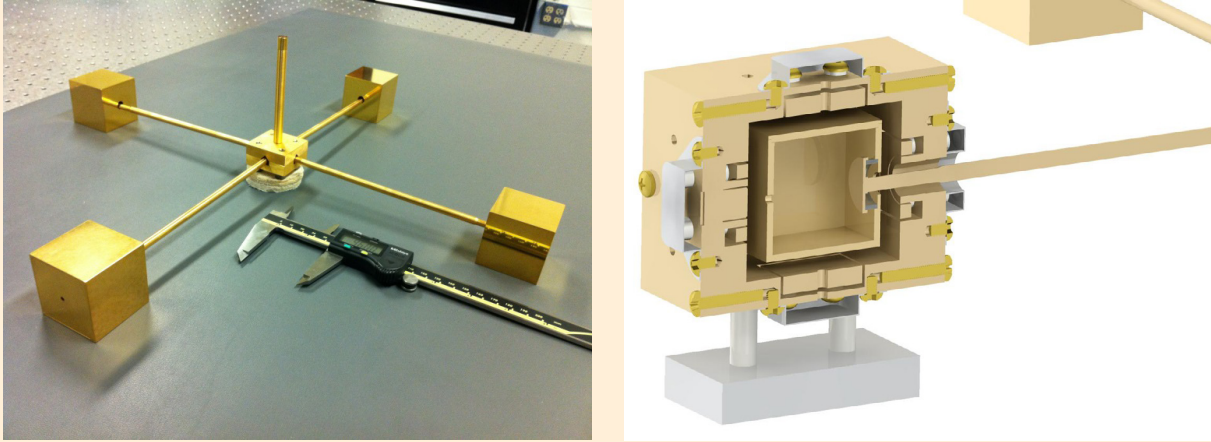


Figure 2: Left: Fit-up test of the four-proof mass structure at the University of Florida. Right: The design of the six-electrode stiffness compensator with hollow proof mass inside.

The proof mass structure, to be consistent with LPF, should consist of four thin-walled hollow aluminum proof masses, 46 mm on a side, and connected by 10 to 20 cm-long shafts to a central block. Following the Trento design, this central block would be connected to a vertical shaft that will be epoxied to the fiber. The proof masses have to be electrically isolated from the rest of the structure. This allows measurement of TM charge-related acceleration noise and testing of the charge management system. The entire structure should be coated with gold on top of a thin sticking layer like titanium or nickel. Figure 2 shows pictures of the existing components at the University of Florida.

The GRS electrode housing will be tested at one of the four proof masses. The opposing proof mass will be encompassed by a stiffness compensator (STC). The stiffness compensator is required to balance the coupling between the pendulum structure and the GRS electrode housing. The STC also allows for differential actuation and differential capacitive sensing of the pendulum angle. The other two proof masses create a mass quadrupole moment which reduces the sensitivity of the torsion pendulum to gravity gradients. These proof masses will also be used as references for an independent optical readout system which is used to calibrate the capacitive readout system and can be used to develop an optical readout which can later be integrated into the GRS housing.

The goals of such a testbed are at least threefold. First, it is necessary to improve our understanding of the European GRS. The GRS is not an isolated system like a detector head or a camera, but interacts with the entire payload. In fact, the main concern about LISA-like missions is their complexity; LISA requires many closed-loop interactions between various subsystems, unlike most other missions either NASA or ESA has flown before. A very detailed understanding of the GRS is needed to understand the resulting interactions and dependencies.

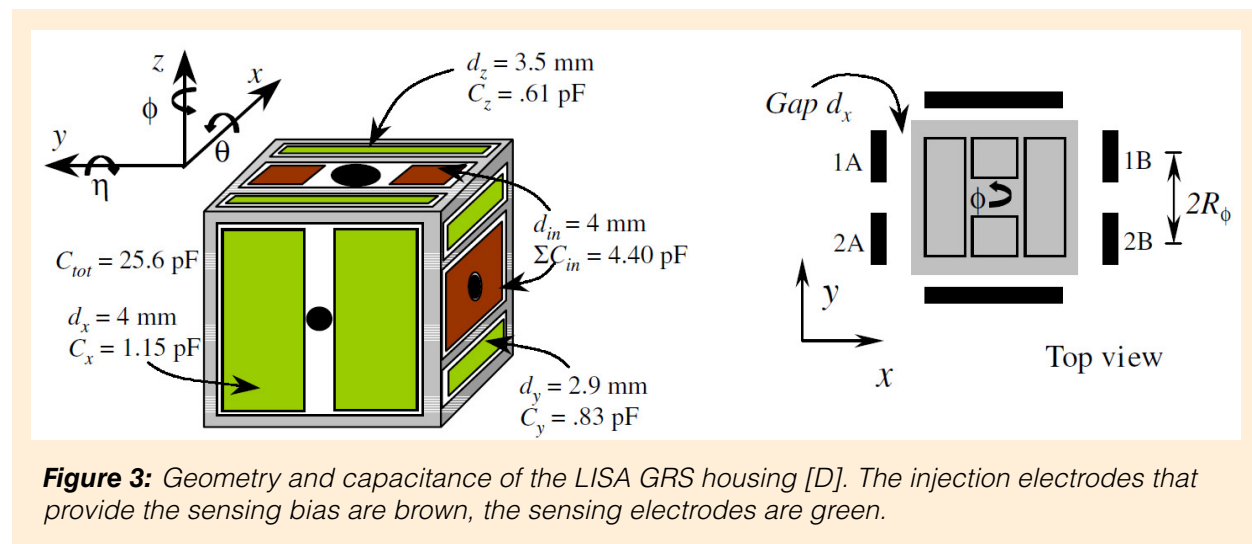
Second, the development of the testbed will start creating a technology and vendor base for the hardware in the U.S. This will bring NASA into a position to fly their own GW mission without relying on European vendors. If LPF is further delayed and ESA selects a different mission for L2, a LISA-like GW observatory has to be one of the favorite strategic missions for the next Decadal in the U.S., following the likely detection of GWs by the Laser Interferometer

Gravitational-Wave Observatory (LIGO) well before 2020. However, the reliance of this mission on several single foreign vendors for the GRS has to be seen as a programmatic risk, especially if there are delays on LPF caused by problems with exactly these vendors. Furthermore, NASA should also look beyond LISA and start to understand what the limiting noise sources of a GRS are and how to overcome them to further improve the sensitivity of LISA-like missions.

The third goal is to provide a testbed where different technologies can be tested. While a successful LPF launch will freeze the basic design of the GRS—such as size and type of proof mass, electrode configuration, gap size, and materials—many more peripheral technologies can and will need to be improved to increase reliability, reduce mass, power consumption, and ultimately cost and risk. These technologies are potential NASA deliverables for eLISA and are certainly needed for a NASA-led mission; e.g., it is nonsense to assume that NASA or ESA would want to fly mercury discharge lamps instead of UV-LEDs in 2028.

Electrode Housing

Like the LPF GRS [C], shown in Figure 3, the GRS will assume a 1.96 kg, 73%/27% gold/platinum cubic proof mass inside a molybdenum electrode housing. Each test mass is 46 mm on a side with a 4 mm gap between the proof mass and the housing. The inside of the electrode housing will be gold coated, and gold-coated sapphire electrodes will be attached to the walls. The electrode geometry and capacitances of the electrodes on the inside surface of the housing are the same as for LISA [D] and are shown in Figure 3. Six “injection electrodes” are driven with a 100 kHz AC bias to frequency shift the capacitive measurement to high frequency. Output of opposing, sensing electrodes are combined via a capacitive bridge. The capacitive sensing scheme will be able to monitor all six degrees of freedom of the PM. High-voltage signals are also injected into the electrodes to actuate the proof masses via electro-static actuation.



Charge Management System

Positive and negative charges accumulating in the proof mass couple to imbalanced DC biases on opposing faces of the housing to produce a ‘random walk’ force noise. Test-mass charging is caused by highly energetic particles that penetrate through the spacecraft and either directly or via secondary electron emission charge the test mass, leading to charging rates on the order of -50 e/sec depending on spacecraft size, shielding provided by the proof mass housing, and

orbit. The caging and uncaging process can also leave behind residual charges on the proof mass. The requirement for maximum proof mass charge for LISA is 10^7 e [F].

A charge management system (CMS) is therefore required for the LISA GRS and is achieved through UV photoemission. LISA Pathfinder will use the 254 nm UV line of mercury lamps as the light source. Measurement of the proof mass charge is performed by applying a dither voltage to opposing electrodes and measuring the resultant PM displacement, which is dependent on the PM charge. However, such applied voltages introduce additional force noise which must remain below the required level if performed during science mode.

In the current LPF CMS design, UV light is directed via a UV fiber feedthrough toward the PM surface if the goal is to increase the PM potential, or directed toward the electrode housing surface if the goal is to decrease the PM potential. Attempts to demonstrate bi-polar charge control using this technique at the torsion pendulum facility in Trento have been only partially successful. This is due to the fact that the work functions of the PM and electrode housing surfaces vary due to differing preparation techniques and cleanliness. UV light directed toward the PM, for example, is somewhat reflected back toward the housing, and if the work function of the housing is lower than that of the PM, electric charge can flow in the unintended direction.

Deep UV LEDs operating at 240–255 nm are a new UV source for controlling PM charge. Compared to mercury (Hg) lamps, UV LEDs are smaller, lighter, consume less power, have a wider spectrum selection, and a higher dynamic range, with at least an order of magnitude improvement in each performance area. The power output is also very stable, with a lifetime > 30000 hours [G].

The faster modulation rate of UV LEDs, compared with Hg lamps, means that AC charge control is possible. In an AC charge control scheme, housing electrode voltages are modulated synchronously with the UV LEDs at a frequency that is far outside the science band; e.g., above 1 kHz. As a result, electrons emitted from any surface will be directed toward the PM or toward the housing, depending on the relative phase of the electrode and UV LED modulations. The AC charge control method will assure current flow in the correct direction, albeit with an amplitude dependent on the reflectivities and work functions of the surfaces.

The GRS testing facility will demonstrate charge measurement and both AC and DC control with a LISA-like GRS and UV LED light sources. In addition to charge control, the CMS is critical for the evaluation of charge-related forces acting on the proof mass and for determining how gold coating procedures and surface cleanliness affects the quantum efficiency at 240–255 nm and, consequently, the discharge effectiveness.

Optical readout

A few fairly simple optical interferometers are required to monitor the positions of the two proof masses not surrounded by the GRS housing or the STC. These signals can be combined to distinguish between displacement of the entire pendulum and torsional motion. This information is needed to calibrate the capacitive readout and to measure the acceleration noise of the torsion pendulum. This is part of the GRS testbed but not of the GRS.

The optical readout for the GRS should monitor all six degrees of freedom of the proof mass with respect to the optical bench. This readout has to be integrated into the GRS housing without affecting the performance of the GRS; the main concern are changes in the surface

potentials of the housing as seen by the proof mass, which can lead to increased electrostatic accelerations. The added optical access points might also require some changes in the location and size of the capacitive plates in the housing, which are in conflict with the declared goal to fly a GRS that is as close to the LTP GRS as possible. Detailed design work and an experimental demonstration of the optical readout in a LTP like GRS are required to test the optical readout system at TRL 3 to 4.

Electronics

The GRS front end electronics (a) generate the 100 kHz injection signal; (b) differentially read out the sensing electrodes using a balanced transformer circuit, followed by a rectifier and a low-speed analog-to-digital converter (ADC); (c) filter the signal; and (d) use a digital-to-analog converter to produce the highly stable electrostatic actuation voltages. Proof mass position sensitivity will be $1 \text{ nm/Hz}^{1/2}$, in the 0.1 mHz to 1 Hz measurement band. Excess noise discovered in the LPF FEE will limit the acceleration noise performance for LISA unless improvements are made.

Advances in digital electronics since the FEE was first developed in Europe will be utilized. This includes faster field programmable gate arrays (FPGAs) and/or microprocessor-based digital signal processing boards; both can be used to generate the injection signals and demodulate the received signals digitally. The same boards can also improve the performance of the digitally generated actuation signals. Also, the analog signal conditioning parts can be improved by taking advantage of NASA's larger portfolio of space-qualified electronic components, such as better low noise analog amplifier circuits.

The main goals are to reduce the noise, improve the performance, and reduce power consumption and, potentially, mass.

2.5.1.6 Timeline/Duration

Note that the GRS testbed depends on a discharging mechanism and electronics, and their development to TRL 3 or 4 cannot be separated from the development of the GRS testbed. The optical readout for all other degrees is required for the testing of the GRS and will be budgeted and scheduled independently.

Milestones

The GRS development consists of seven main activities:

1. Vacuum system has to be designed and procured.
2. The pendulum structure and electrode housing have to be designed, fabricated.
3. The charge control system has to be implemented.
4. The electronics to sense the position of the proof masses and to actuate on the proof mass have to be tested and integrated into the testbed.
5. A simple optical readout system to calibrate the capacitive sensors and actuators has to be set up.

6. All subsystems have to be integrated and tested.
7. Following all of these steps, the acceleration noise measurements will start. This includes the measurements of multiple transfer functions required to fully characterize, study, and improve the system. This also includes the commissioning and potential improvements of the electronic, the pendulum, the charge control system, and the vacuum system.

Expected duration for the first six activities is about 1 year. The seventh activity includes the main scientific tests and will take about 2 years to complete.

- A full optical readout could be developed in year two and then added to the GRS late in year two or early year three without delaying the main noise measurements.

The schedule for the first 3 years of GRS technology development is shown in Table 2. The schedule assumes a start in the first quarter of 2014 and will result in all GRS components listed in Table 1 elevated to TRL 3-4 by the start of FY 2017.

Table 2—Schedule for GRS Technology Development

Task ID	Task Description	Duration (mo)	Deliverables	Dependencies	Resources		TRL	
					FTEs	Procurement (\$k)	In	Out
1	Vacuum System	3						
2	GRS and Test Facility Development		Complete GRS and test facility assembly		0.75	120	3	3
2.1	GRS design and assembly	12	GRS and pendulum	None				
2.1.1	GRS design	3						
2.1.2	GRS fab and assembly	6		Complete 2.1.1				
2.1.3	GRS integration in vacuum system	3		Complete 1, 2.1.2				
2.1.4	Fabrication of 4 PM structure	6						
2.1.5	Integration of PM structure	1		Complete 2.1.4				
3	Charge Control System Assembly	3	Charge control system	None	0.5	50	3	4
4	Electronics System Design and Fabrication	12	GRS electronics	None	0.75	50	3	4
4.1	Electronics system design	4						
4.2	Electronics fabrication	4		Complete 4.1				
4.3	Electronics test	4		Complete 4.2				
5	Optical Readout System	9	Optical readout system	None	0.75	50	3	4
5.1	Optical readout system design	2						
5.2	Optical readout system fab	6		Complete 5.1				
5.3	Optical readout testing	1		Complete 5.2				
6	GRS Testing and Noise Measurements	24	GRS functional test and acceleration noise report		2.5	20	3	5
6.1	Pendulum functional test	3		Complete 1, 2, 3, 4				
6.2	Initial noise measurements	3		Complete 5, 6.1				
6.3	Measurement of individual noise sources	9		Complete 6.2	2.5	10		
6.4	Estimation of total acceleration noise	3		Complete 6.3	2.5	10		

2.5.1.7 Budget

Procurement costs: \$250k (without optical readout), 120k for optical readout

- Labor: 2.5 FTEs
- Duration: 3 years

The goals of the GRS testbed are to:

- Enable tests of GRS components
- Gain experience in the U.S.
- Develop a vendor base in the U.S.
- Reach TRL 3 for the UV-LED discharge system
- Reach TRL 3 for the new and improved electronic
- Reach TRL 3 for the optical readout (if added)

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2.6 Micro-Thrust Propulsion

Function and Role in the Flight System: Micro-thrust propulsion is required for all future space-based gravity wave observatory (SGO) mission scenarios, including the European New Gravitational-wave Observatory (NGO), NASA's SGO-Mid, Lagrange, and Omega, to negate orbital disturbances other than those due to gravitational waves, mostly solar pressure induced. Required thrust levels range from 30 to 150 μN , depending on mission scenario. Lifetime requirements range from 2 years (minimum) to potentially desired extended mission scenarios of up to 5 years.

Different micro-thrust propulsion options exist (see the "Other Micro-Thrust Developments" subsection). The most mature option, scheduled to fly on the Astronomy and Astrophysics Space Technology 7 Disturbance Reduction System (ST7-DRS) mission, is a colloid propulsion system developed by Busek Co., Inc. (Fig. 1). It consists of two clusters of four independent thruster systems. Each thruster system includes a thruster head with nine needle emitters and electrodes that extract and accelerate the propellant (Fig. 2), a pressurized bellows feed system that regulates the propellant through a precision flow-control microvalve to the thruster head, and high voltage electronics (up to 10 kV). This system is integrated on the Laser Interferometer Space Antenna (LISA) Pathfinder spacecraft, which is awaiting launch in 2015. This feed system, while sufficient for the relatively short duration ST-7 mission, will be upgraded to handle larger propellant loads for actual gravitational wave (GW) missions, in particular for extended-mission scenarios through a recently selected Strategic Astrophysics Technology (SAT) technology development effort. A carbon nanotube cathode neutralizer, developed by Busek, provides beam neutralization.

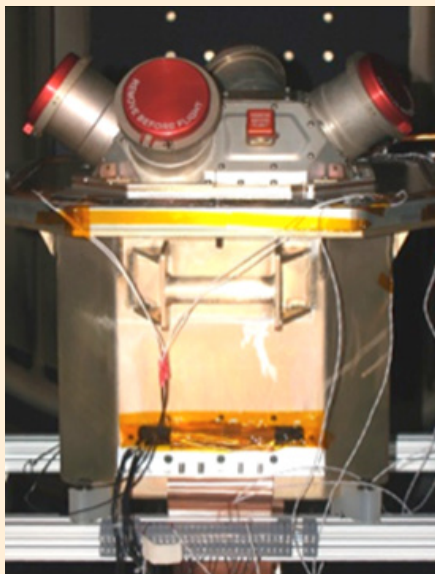


Figure 1: Busek Colloid Micro-Newton Thruster (CMNT) cluster with four independent thruster systems.



Figure 2: Busek CMNT thruster head and single emitter (9 emitters per thruster head).

Baseline Architecture: The Disturbance Reduction System (DRS) for each spacecraft consists of position sensors, micronewton thrusters as actuators, and drag-free control laws that maintain the spacecraft orbits and cancel out the environmental disturbances (mainly solar photon pressure) to the spacecraft (Fig. 3). Colloid microthrusters fire to oppose external forces, which are primarily due to solar radiation pressure acting on the spacecraft solar panel. The thrust will be continually adjusted to keep the spacecraft centered about the test masses.

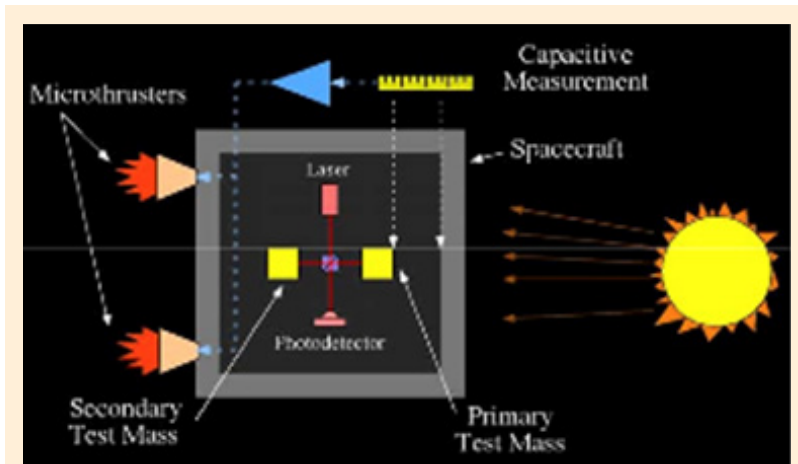


Figure 3: Concept of the Disturbance reduction System (DRS) including microthrusters.

Requirements and Risks: Propulsion performance requirements to accommodate DRS requirements are summarized in Table 1, comparing ST-7, LISA, and SGO-Mid requirements. It is assumed that future NGO mission requirements are similar to those for LISA. The thrust range requirement is determined by the need to counter the solar radiation pressure on the spacecraft and provide any tip-off, orbital maintenance, or safe-mode support. The thrust noise and resolution requirements are needed to meet the spacecraft position control requirement, with the upper frequency range of the thrust noise specification being extended to 5 Hz to accommodate the control loop. The ST-7 thruster operational lifetime includes the 90-day mission design; but the design lifetime is set at 3,300 hours to accommodate a standard 50% thruster lifetime margin.

Table 1—NM ST-7 and LISA Precision Propulsion Requirements.

Requirement	ST7	LISA	SGO-Mid	eLISA
Thrust Range	5–30 μN	4–30 μN	4–150 μN	4–150 μN
Thrust Precision	< 0.1 μN	< 0.1 μN	< 0.1 μN	< 0.1 μN
Thrust Noise	< 0.1 $\mu\text{N}/\sqrt{\text{Hz}}$ (5 Hz control loop)	< 0.1 $\mu\text{N}/\sqrt{\text{Hz}}$ (5 Hz control loop)	< 0.1 $\mu\text{N}/\sqrt{\text{Hz}}$ (5 Hz control loop)	< 0.1 $\mu\text{N}/\sqrt{\text{Hz}}$ (5 Hz control loop)
Thrust Command Rate	10 Hz (< 0.1 s latency)	10 Hz (< 0.1 s latency) (TBC)	10 Hz (< 0.1 s latency) (TBC)	10 Hz (< 0.1 s latency) (TBC)
Thrust Range Response Time	< 100 s	< 100 s (TBC)	< 100 s (TBC)	< 100 s (TBC)
Specific Impulse (30 μN point)	> 150 s	> 150 s (TBC)	> 150 s (TBC)	> 150 s (TBC)
Specific Impulse (6 μN point)	> 275 s	> 275 s (TBC)	> 275 s (TBC)	> 275 s (TBC)
Operational Lifetime	> 2,200 hours	> 55,000 hours	16,000 hours	16,000 hours
Plume Half Angle	< 35° (95% beam current)	< 35° (95% beam current) (TBC)	< 35° (95% beam current) (TBC)	< 35° (95% beam current) (TBC)

The biggest difference between the LISA and ST7 requirements is operational life; thus, this is the most important area of technology work remaining after the ST7 mission. In the case of a NASA-led, SGO-Mid-based mission scenario, another major difference in requirements will be thrust range, possibly extending up to 150 μN , and thus requiring an entirely new thruster head with additional emitters and a micro control valve modified for larger flow rates.

Embedded in these additional requirements (lifetime and thrust range) are risks associated with the development of these capabilities. These include:

1. Understanding, modeling, and measuring thruster “overspray” (small fractions of the beam current, <1% of the exhaust at the outer edge, impinging on the electrodes), which may lead to electrical shorting in the thruster over time.
2. Microvalve range and reliability, including extending flow-rate capability and cycle life without developing leakage over time.
3. Scaling up the thruster system, likely through a combination of increasing the number of emitters, emitter size (current/emitter), increased microvalve flow capability, and increased neutralizer currents.

All systems will require increased propellant mass for even the baseline 2-year mission scenarios considered, and even more so for extended mission scenarios. The current bellows-based feed system architecture will no longer be feasible due to significant mass increases, limited vibrational stiffness when scaling up, and an increased source of bubble formation due to ever larger internal surfaces, introducing major thruster reliability concerns. Under the Physics of the Cosmos (PCOS) SAT program, all-metal diaphragm tanks and associated feed system hardware and loading procedures will be developed.

Status: Currently, ST7-DRS has qualified and integrated two four-thruster units for use on the LISA Pathfinder (LPF) spacecraft. The ST7-DRS thrusters have demonstrated (through ground testing):

- 4.35–35.8 μN thrust range ($> 36 \mu\text{N}$ for short durations)
- 0.08 μN thrust precision (measured), 0.01 μN (calculated)
- 3460 hours of lifetime, including 2160 hours using an expected thrust profile

The LISA Microthruster Technology Program focused on extending the ST7-DRS thruster lifetime to 5 years. During this program, the following tasks were accomplished:

- Failure mechanisms were identified and categorized based on their impact and likelihood through analysis, testing, and ST7 experience.
- Six single-emitter thrusters, with slight variations in design, were run in parallel for 3000 hours to help validate failure mode identification and feed system cleanliness and contamination requirements.
- The lifetime limit of propellant being deposited onto the electrodes was evaluated through modeling and test work.
 - Propellant loading of the accelerator and extractor frits and subsequent shorting was identified as the highest lifetime risk.
- The deposition rate of propellant onto the electrodes was measured down to 10 nanoamps and 50 nanogram/second resolution over an extended operating range at various temperatures.
 - Only single-emitter tests under steady state conditions were performed; multi-emitter thrusters under time-varying voltages and currents may lead to different results and remain to be verified.
- Lifetime models and estimation tools were developed using the lifetime limits of the electrodes, deposition rate measurements, and expected thrust profiles.
 - Thruster lifetime was found to be a major function of operational time at maximum thrust, with lower thrust levels significantly improving lifetime.

- ▶ Lifetime estimates came out near 40,000 hours for expected thrust profiles, with 40% uncertainty due to the use of acceleration factors and facility effects.

Most recently, under the PCOS SAT program, NASA's Jet Propulsion Laboratory (JPL) was awarded a project to scale up micro-thruster feed system to handle increased propellant loads as expected under the mission scenarios considered here (NGO and SGO-Mid) (Table 2). In this activity, the bellows assembly of the ST-7 system will be replaced with an all-metal diaphragm tank, the design of the flow control valve will be upgraded to improve manufacturability and reduce fabrication rejection rates, and a feed system with valve isolation and redundancies will be assembled and tested (Fig. 4). Propellant loading and flow control schemes will be studied. The SAT project will not include the integration of micro-thrusters, and thus a full end-to-end test of a micro-thruster system. These tasks remain to be accomplished in a follow-on program to study thrust control via flow control, and voltage isolation of the system using an electrically conductive, high-voltage floating propellant.

Table 2—Propellant mass requirements per thruster for different gravity wave mission concepts demand larger tanks.

	ST7-DRS		LISA		SGO-Mid/eLISA (2-year)		SGO-Mid/eLISA (Ext. 5-year)	
	Science	Attitude	Science	Attitude	Science	Attitude	Science	Attitude
Average Thrust (μN)	20	N/A	10	30	10	30–150	10	30–150
Duration (hrs)	1400	0	60000	6000	16000	1800	40000	4000
Total Impulse (Ns)	100		2800		800–1200		1900–2900	
Propellant Mass (kg)	0.06*		1.5		0.4–0.6		1.0–1.5	

* ST-7 propellant tanks are sized for full thrust, 30 μN , for 90 days, 0.15 kg of propellant.

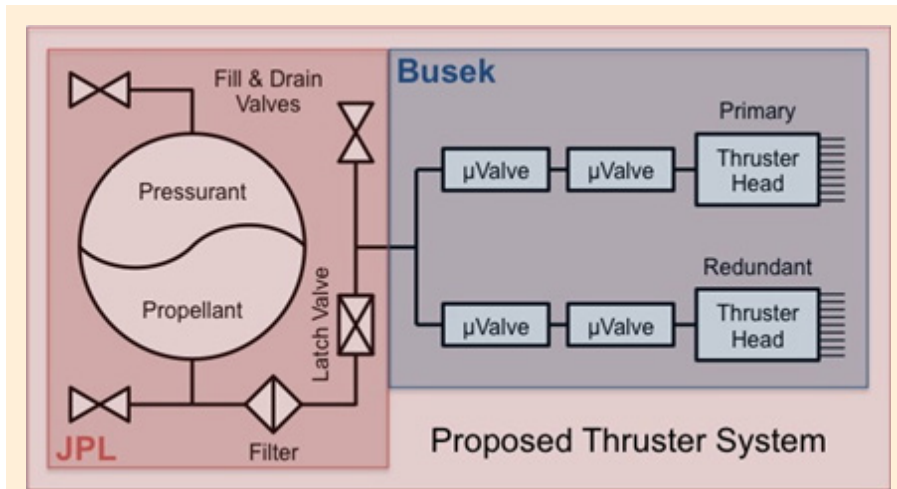


Figure 4: Schematic of the PCOS SAT feed system, including a diaphragm tank developed by JPL that will reduce the mass of the system by more than 50% compared to a scaled up bellows architecture.

Table 3 lists a TRL breakdown of the current 30 μN ST-7 thruster system for a targeted 2-year mission life, a future, scaled up 150 μN thruster concept for a 2-year mission life, and a 30- μN thruster system for an extended mission life of up to 5 years. The propulsion subsystem TRL was assumed to be lowest of its subsystems (thruster head, feed system, and power processing).

Table 3—Thruster System TRL Breakdown

Thruster Configuration & Lifetime	TRL			
	Thruster System	Thruster Head	Feed System	Power Electronics
30 μN , 2-yr thruster life	3	5	3	5
150 μN , 2-yr thruster life	3	3	3	3
30 μN , 5-yr thruster life	3	4	3	5

Other Micro-Thruster Developments: Other thruster technologies currently that have been under development for the LPF and NGO missions include Cesium (C_s) Field Emission Electric Propulsion (FEEP) thrusters by ESA in Italy. Most recently, C_s -FEEP thrusters have been eliminated as an option for LPF due to lifetime and performance issues related to the physics of the cesium propellant. Significant challenges persist in handling the cesium propellant during startup without clogging emitter slits due to formation of cesium hydroxides due to its interaction with water content in the atmosphere, or shortening grids from evaporating propellant and thus significantly increasing lifetime risks. As an alternative, cold gas systems

are now being designed to replace the C_s -FEEPs on LPF. These systems operate at substantially lower specific impulses, requiring higher propellant mass and large as well as heavy (high-pressure) tanks, and potentially posing leakage risks given high-pressurant gaseous propellant storage over long mission durations. Miniature ion thruster options have been considered, both using radio frequency (RF) as well as DC operation, and are under development in Europe as well as various institutions in the U.S. (Busek, Inc., Pennsylvania State University, and JPL). All are under laboratory development at this stage.

Development Tasks to TRL 5: Based on the information provided in the previous subsection, clearly estimating and possibly extending thruster lifetimes to meet extended mission goals is a key issue that remains to be addressed. This includes subsystem components, such as the control valves, as well as feed system integration to be able to process the additional propellant load. Since thrust range also will need to be extended to meet newer SGO mission scenario requirements, lifetesting of the thruster should follow a decision on thrust level and thruster development to meet this requirement. This decision should be taken as soon as possible in order to initiate lifetesting prior to any future flight project start, as it is likely not to be accomplished under typical flight project schedule constraints. Feed system scaling and valve lifetime test are less sensitive to thruster and could be initiated immediately. Thruster technologies other than colloid systems face additional technology risks that would need to be addressed for them to be considered back-up options or contenders to colloid systems.

The following development tasks are therefore being proposed for consideration in future technology development activities:

1. Thruster feed system scaling:

Key elements of the colloid thruster feed system are its propellant reservoir, piezo-electrically actuated thruster flow control microvalves, as well less critical supporting hardware, such as fill and drain valves. For extended mission periods, the feed system needs to be scaled up, and additional redundancy be provided, to support the required propellant throughput and operating lifetime. The current bellows assembly is no longer mass effective for larger propellant loads, and is a source of lifetime limiting bubble formation in the propellant. A diaphragm tank based approach will need to be developed.

Funding of \$1.4 million (M) has been obtained by JPL to conduct key aspects of this development task. This will include tank design and feed system integration, but not complete integration with the colloid thruster heads. *Note that this task describes the follow-on work required to integrate thrusters with the feed system, operating the system in a thrust-controlled fashion, and facilitating high-voltage isolation of the system and its various feed system components, which may include re-design of commercial off the shelf (COTS) valve parts and pressure transducers and newly design mounting.*

Impact: Scaling the feed system to larger propellant loads and providing improved valve lifetimes and redundancies will allow for extended mission periods and reduce risk.

Cost: Labor: 2 full-time equivalent (FTE), Procurements: \$500k

Schedule: 1 year

1.1 Thruster Integration:

Integrate the SAT derived feed system with two micro-thrusters demonstrating end-to-end operation in a thrust controlled mode.

1.2 COTS Component High-Voltage Redesign:

Work with the vendor to derive component designs able to handle a conductive ionic liquid propellant floating at high-voltages (up to 10 kV). Basic materials compatibility will already be addressed under the SAT program.

1.3 High-Voltage Isolation:

Develop high-voltage isolation (up to 10 kV) schemes for tank and feed system mounting, while maintaining structural mounting requirements with respect to shock and vibration requirements, as well as thermal requirements.

2. Microvalve Lifetime:

Current ST7 microvalves have been qualified for 90-day operational lifetime. A simplified, more reliable, and easier to manufacture microvalve design, currently being developed under a NASA Phase II Small Business Innovative Research (SBIR), will need to be fully developed and its lifetime demonstrated. Functional testing, full propellant through-put test, long-term propellant compatibility (in particular with soft goods), valve cycling capability, and leakage rates need to be determined and optimized for desired mission life, included extended mission durations.

Impact: A more reliable microvalve design reduces valve reject rates and costs, and reduces mission risk if verified for the desired mission lifetime.

Cost: Labor (JPL): 0.2 FTE, Contract (Valve Vendor): \$550k
Schedule: 2 years

3. Extension of Thrust Range to 150 μ N:

Recent mission studies determined thrust ranges of up to 150 micro-N for some mission scenarios (SGO), extending the current ST-7 thrust range by a factor of five. Thrusters thus need to be scaled up to provide sufficient thrust levels for future gravity wave observatory missions. This includes thruster and microvalve. Here, a TRL goal of 4 at the end of this task is assumed, allowing for substantial maturation of a scaled-up thruster version, yet allowing flight projects to further refine thruster requirements prior to higher level maturation.

Impact: Providing larger thrust range will meet thrust range requirements of future mission scenarios such as SGO-Mid and SGO-High.

Cost to TRL 4: Labor: 2.5 FTE, Procurements: \$300k
Schedule to TRL 4: 1 year

3.1 Thruster Scaling:

Extending the thrust range will require a thruster redesign, including either additional emitter capillaries to be arranged in an array, larger capillaries, or (most likely) a combination thereof.

3.2 Microvalve:

The microvalve will need to be redesigned to support the required higher flow rates corresponding to the upper end of the thrust range. Piezo-actuator strokes in particular are limited, potentially requiring mechanical stroke amplification.

4. Thruster Lifetime:

Extended mission lifetimes of 5 years no longer allow for full lifetime testing, including margin, within typical project schedules. Therefore, a combination of physics-based thruster modeling identifying thruster wear-out failure modes, experimental model verification, and accelerated lifetime testing is being proposed. This goes above and beyond the work conducted under the LISA microthruster technology development activities due to the extended thrust range requirements. Since these models will eventually be used as justification for the thruster lifetime along with shorter-duration tests, the uncertainty in the models and measurements must also be reduced.

Impact: Addressing thruster lifetime will enable future extended missions and reduce risk for all mission durations.

Tasks 4.1–4.3: Cost: Labor: 3 FTE, Procurement: \$250k
Schedule: 1 year

Task 4.4: Cost: Labor: 3 FTE, Procurement: \$250k
Schedule: 1 year

Task 4.5: Cost/year: Labor: 3 FTE, Procurements: \$100k
Schedule: >1 year as funding permits and thruster operates

4.1. *Physics-based thruster modeling:*

A potential lifetime-limiting threat to colloid thrusters is overspray, where over time sufficient amounts of propellant accumulate on thruster accelerator grids to generate spray-back or even a conductive short to the emitter. A physics-based model of the thruster plume (current density, ion and droplet q/m) will allow determination of propellant flow intersected by the grid under different operating conditions. The plume models need to be complemented by capillary flow models of the condensed propellant on the grids, and across insulators and various other thruster surfaces. While some modeling was performed under LISA, models need to be refined and adapted to future thruster geometries including multi-emitter geometries, emitter size (in case of scaled up devices), thruster grid geometry, and non-steady state thruster operation.

4.2. *Model Verification:*

The above model will need to be verified in short-duration (1000s of hours) testing compatible with anticipated technology development and project plans. Once verified, models may be used to estimate thruster lifetimes over extended mission periods. Initial experiments were conducted under LISA for single emitters; however, future experiments needs to be adapted to multi-emitter geometries, time-varying thruster profiles, and diagnostics of the test set up needs to be improved.

4.3. *Accelerated Lifetime Testing:*

Using model-based predictions, the expected propellant quantity corresponding to the desired lifetime will be deposited onto the various thruster surfaces, including thruster grid, and determine back-spray characteristics and potential of propellant migration/shorting during anticipated thruster operation.

4.4. *8,000-hour thruster life test:*

At least one full thruster life test should be conducted in parallel to tasks 1.1–1.3 to ensure detection of any unforeseen life-limiting events; i.e., potential emitter clogging or power processing unit (PPU) lifetime issues. This test will target 8,000 hours of thruster operating time at representative thrust cycles, and allow for further verification of modeling and accelerated life test, corrections as needed, and repeat of tasks 1.1–1.3.

4.5. *Extended thruster life test:*

Subsequent to the 8,000-hour test, this test may be extended by operating the existing thruster hardware in the existing test facility further, as long as desirable or thruster operation permits. This will allow for potential changes in thruster requirements, imposed by an actual mission, to be integrated. Since extended SGO mission duration may be many years (up to 5 years), further risk will be reduced by running a thruster for the actual mission duration, or a substantial fraction thereof, allowing for the potential of unknown life-limiting factors to be discovered and evaluated. No project schedule will allow for such an extended life test; however, if initiated under a technology program prior to or early in the project schedule, substantial risk mitigation may be derived from such a test.

5. Evaluation of Competing Thruster Technologies:

Building on the extensive thruster development and system integration expertise accumulated under NM ST-7/LPF, existing expertise and facilities—e.g., thrust stand, ultra-high vacuum (UHV) test facilities, plume measurements—may be applied to other competing thruster technologies under investigation as back-up micro-thruster options, including, but not limited to DC or RF-micro-ion thrusters or cold gas systems, either U.S.-based or from abroad. There is precedence of such work—initial testing approximately a decade ago included testing and evaluation of Austrian-built Indium FEEP thrusters at JPL.

The NASA SBIR program should be integrated into this effort to allow for promising alternative thruster options to be evaluated, and JPL thrust stand, UHV, or other diagnostics facilities maybe provided as government-furnished equipment to evaluate these thruster concpets in an objective fashion.

Cost/year: Labor: 1 FTE, Procurement: \$100k

Table 4— Thruster Development Tasks

Task ID	Task Description	Duration (mo)	Deliverables	Dependencies	Resources		TRL	
					FTEs	Procurement (\$k)	In	Out
1	Thruster Feed System Scaling	12			2	500	3	4
1.1	Thruster integration			None				
1.2	COTS component high-voltage redesign			None				
1.3	High-voltage isolation			None				
2	Microvalve Lifetime	24		Must complete 3.2 before completion of this task	0.2	550	3	5 (microvalve)
3	Extension of Thrust Range to 150 μN	12			2.5	300	3	4
3.1	Thruster scaling			Mission design defined				
3.2	Microvalve redesign			Complete 3.1				
4	Thruster Lifetime	24+		Complete tasks 1, 2, and 3	6+	500+		5 (thruster subsystem)
4.1	Physics-based thruster modeling	12			3	250		
4.2	Model verification							
4.3	Accelerated life testing							
4.4	8,000-hour thruster life testing	12			3	250		
4.5	Extended thruster life test	12+			3/yr	100/yr		
5	Evaluation of Competing Thruster Technologies	12			1	100		

2.7 System Validation and Testbeds

This section addresses the strategy for tracing the mission and component requirements to the Laser Interferometer Space Antenna (LISA) science return and describes the use of testbeds and simulations to retire risks at different levels of functional interaction. Activities funded outside the LISA efforts promise substantial risk reduction for LISA as described herein.

Science Traceability

As with the Gravity Recovery and Climate Experiment (GRACE), Gravity Recovery and Interior Laboratory (GRAIL), and GRACE Follow-On missions, LISA relies on measurements from distributed non-interacting spacecraft to produce observables that are used in a quantitative analyses to extract the science return. As with those missions a representative system test is not possible, but a powerful set of analysis tools combined with lower-level tests and testbeds can produce a robust traceability of the mission performance to the expected science return. Figure 1 demonstrates at the top level a snapshot of this hierarchical flow of traditional lower-level component performance, combined with testbeds and simulations targeting specific levels of functional integration, to retire identified risks and to uncover unknown risks in the mission architecture.

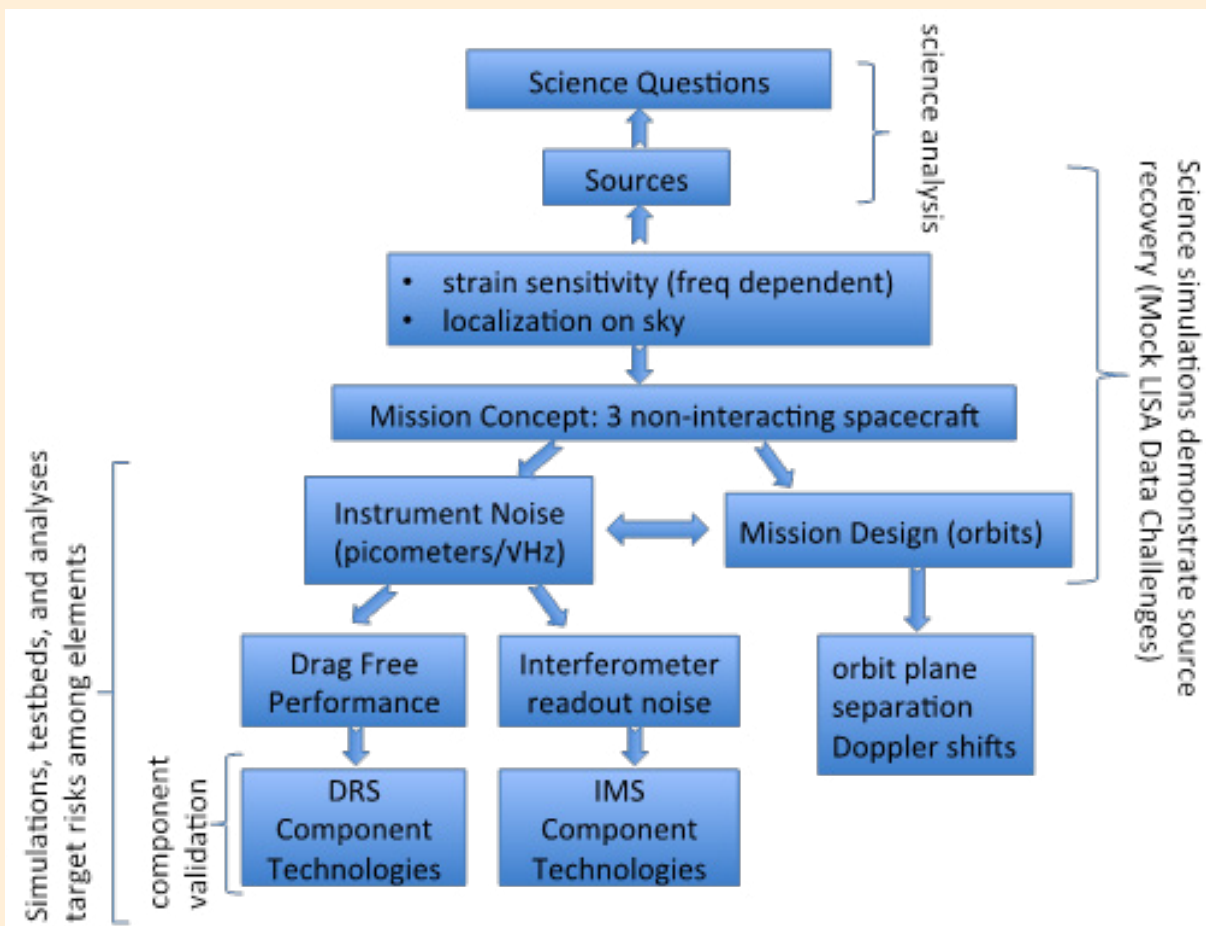


Figure 1: LISA follows a similar validation approach to previous “constellation-as-instrument” missions such as GRACE and GRAIL.

Science Simulations: the Mock LISA Data Challenge

Identified Risk: Scientists may not be able extract individual source parameters amidst the forest of signals and in the presence of instrument noise

LISA will see a source-rich collection of gravitational wave (GW) signals throughout the sky. Where Laser Interferometer Gravitational-Wave Observatory (LIGO) will be challenged to identify a signal within the noise, the challenge for LISA is to identify individual astrophysical sources. To meet this challenge, LISA scientists have developed a Mock LISA Data Challenge, in which source signals are added to observables generated through Synthetic LISA, a tool for propagating orbits and simulating the Time Delay Interferometry (TDI) observables with noise from unsuppressed forces acting on the proof mass, and including readout noise from the interferometer link. Participants worldwide then try to perform parameter estimation for the signals (see e.g., [Mock-2010]). These simulations serve the role of the Mirage gravity-recovery software used on GRAIL, in which simulations can be used to tie mission performance to science return, and the tools used in the simulation are then used for science signal recovery during operations. Synthetic LISA was used with the instrument observable hardware simulation capability of the LISA phasemeter in hardware-in-the-loop simulations that connect the Synthetic LISA observables to the laboratory demonstration of TDI [Testbed-2010]. Other science simulators have been developed by other scientists [Simulator].

Risk Reduction and Validation through simulations and testbeds

While no representative system-level tests are possible for distributed spacecraft, and in particular for drag-free technologies, testbeds can be used to amplify sensitivities and produce tests that would not be possible even with a system-level test. In general, as is often the case in precision measurements, the use of laboratory hardware with enhanced signals produces more significant results than using highly representative hardware. The following subsections provide examples of the use of dedicated testbeds to target specific risks, imagined testbeds for probing unknown risks, and simulations to address system-level interactions.

GRS testbeds

Identified risk: Inability to test a free-floating proof mass on the ground might hide performance-limiting effects.

MicroNewton thruster test stand

Identified risk: Gravitational Reference Sensor (GRS) performance relies on thrust force behavior at low thrust and at low Fourier frequency that are difficult to measure.

Like many aspects of LISA, the performance of microNewton thruster technologies benefit from significant modeling efforts of the behavior of the thrusters under a variety of conditions, but measurements are required to validate the models. To support the thruster modeling efforts and to verify performance of individual thrusters, a test stand was developed giving the capability to verify low thrusts at the long times (low Fourier frequencies) relevant for LISA. This allows direct verification of the thrust performance of thrusters under a variety of conditions and supports lifetime and model-based testing.

TDI testbed

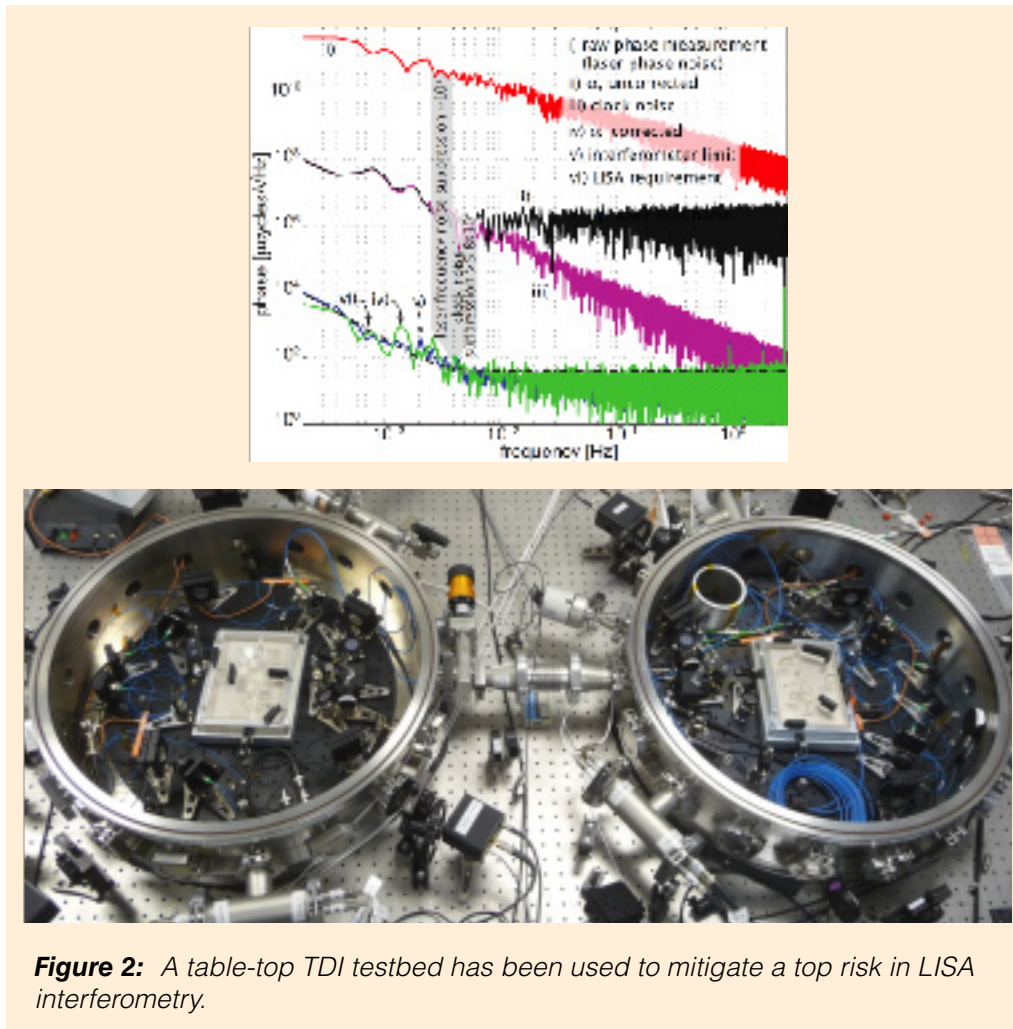
Identified risk: *The 2005 LISA Technology Development Plan identified the unproven corrections of laser frequency noise and clock noise in TDI to be a top risk in the Interferometric Measurement System (IMS).*

LISA interferometry relies on precise measurements of the phase of laser heterodyne beatnotes combined in post processing to remove the impacts of laser frequency noise using TDI. Laser frequency noise enters because the distributed spacecraft cannot maintain an equal arm “white light” interferometer configuration and, in addition, noise from the sampling clocks enters due to the multiple changing heterodyne frequencies introduced by the orbital propagation of the spacecraft. These characteristics have been implemented in a TDI testbed that combines the following elements of interferometry: picometer metrology with laser beam combinations similar to those to be used in flight, clock noise correction, nanoradian wavefront sensing, centimeter-level absolute ranging, laser pre-stabilization, suppression of residual frequency noise based on TDI, and combining separate phase measurements to form GW observables using high-resolution interpolation. It will also serve as a platform for testing incremental development of electronic, mechanical, and optical hardware identified in other sections of this plan.

The LISA interferometry testbed, shown in Figure 2, has already addressed several of the required interferometry technologies. That testbed was guided by the latest technology plan [Tech-2005], which identified the lack of an interferometry demonstration as the top risk to LISA technology development. Table 1 lists the milestones from that plan to address the risks, with new columns indicating the current level of completion of the milestones (Full or Partial). The milestones listed as partially complete are represented by experimental results [Testbed-2010] that surpassed the requirement sensitivity level of $400 \mu\text{cycle}/\sqrt{\text{Hz}}$, but did not meet the [Tech-2005] goal level of $13 \mu\text{cycle}/\sqrt{\text{Hz}}$ ($1 \mu\text{cycle}$ corresponds to 1 pm). The achieved sensitivity was approximately $40 \mu\text{cycle}/\sqrt{\text{Hz}}$. Figure 2 also shows the demonstration of suppression of frequency noise by TDI by a factor of 10^9 , which is larger than the original requirement and which therefore allows relaxation of laser prestabilization. It also shows clock noise suppression at the required level of 10^4 .

Table 1—Incomplete TDI Testbed Milestones from the 2005 LISA Technology Development Plan

Gates	Reference	Comments	Partial	Full
Interferometry demonstration (TRL 3)	IG-1	IMS ITAT top risk. Performance assumptions form foundation of measurement concept.		
Laser frequency noise correction	ISM-5	Intermediate milestone for IG-1		
Clock noise correction	ISM-7	Intermediate milestone for IG-1		
Ranging, clock offset measurement, and optical communications impact	ISM-8	Intermediate milestone for IG-1		



The planned effort is an extension of [Tech-2005], intended to demonstrate TDI with improved performance and using component technologies of higher TRL. Elements of the plan are listed herein.

To assure that shot noise is the dominant limit to sensitivity, an integrated testbed will need to demonstrate TDI with better sensitivity than has been achieved so far. The target level of sensitivity with high optical power is $3 \text{ pm}/\sqrt{\text{Hz}}$ in TDI observables, and shot-noise limited sensitivity of approximately $10 \text{ pm}/\sqrt{\text{Hz}}$ with representative laser signal power. The demonstration will include clock noise suppression, and frequency noise suppression based on absolute range measurements at the level of 10 cm or better, nanoradian-level differential wavefront sensing (e.g., see [LPF-ifo-2011]), high-dynamic range μcycle phase measurements, and high-resolution interpolation to form the TDI signal.

Additional work on testbeds relevant for TDI have been developed at other laboratories in Europe and in the U.S., some focusing on introducing an electronic phase delay [EPD, UF-SIM].

“Relevant environments”

Identified risk: *Requirements for component technologies are inadequate for the end-to-end application.*

The TDI testbed described previously was intended to test for the adequacy of the phasemeter requirements in their intended application. Similarly, many components of LISA interferometry may have unanticipated interactions in their requirements and performance that can be best addressed through testbeds of varying complexity.

As an example, the Non-Planar Ring Oscillator (NPRO) master laser in LISA must be frequency stabilized to some reference, while at the same time the optical power on the GRS proof mass must be quite stable to avoid imparting radiation pressure noise. Testing of a commercial NPRO laser in a laser-stabilization system while simultaneously controlling the output power showed incompatibility of these two control systems. LISA naturally separates out the functions of frequency stability and power stability by allowing power stabilization on an external optical amplifier, but verification of this more integrated package in a laser stabilization testbed with phase tracking and amplitude control significantly reduce the risk of unintended consequences at higher levels of integration. In this example, the testbed does not need to include highly representative hardware, but just the ability to exercise the functionality of the laser.

Telescope/optical bench interferometer testbeds

Identified risk: *The optical bench-telescope interface involves critical and coupled alignments.*

Several different types of testbeds support testing of the optical bench and telescope critical alignments; only a few will be described here, with the intent of demonstrating the power of small dedicated testbeds of integrated flight-like or flat-sat testbeds that come traditionally in the flight development.

The telescope assembly requires picometer stability between the primary and secondary mirrors. LISA trade studies have looked at different materials for the spacer, including silicon carbide (SiC) and carbon-fiber-reinforced polymer (CFRP). To understand the first-order sensitivity to material choices, a testbed was built at the University of Florida to measure the stability of the optical support structures using an optical reference cavity built into the structure, rather than building a finished telescope and trying to verify its performance in some large-scale interferometer. Indeed, verification of the stability of a high-fidelity telescope would be much more difficult than such a testbed study.

Studies of the telescope show that it has critical alignment requirements that connect its requirements to the optical bench. In principle these requirements lend themselves to traditional decomposition of requirements, but testbeds offer an early validation that the requirements are complete and to uncover driving requirements. Examples include coupling of angular jitter into piston in the optical chain, or the coupling of the beam launcher to the optical bench and telescope as it relates to pointing and focusing alignments, phase variations, and scattered light implications of structural distortions. Such sensitivity studies are best completed in a testbed that allows exaggeration of effects and rapid design variations, rather than being performed on a linear trajectory of integrated high-fidelity hardware. Such a testbed naturally provides opportunities for testing component hardware as well.

Acquisition Simulations

Early in the LISA development, acquisition of LISA's six interferometer links and drag-free control of the spacecraft, which depends on differential wavefront sensing from the interferometer links, was viewed as one of LISA's greatest risks. Dedicated simulations and studies of this 57 degree-of-freedom acquisition problem using component-level instrument capabilities retired the primary risks of acquisition. These simulations took as inputs unit-level capabilities of items like laser frequency tuning, optical acquisition sensor readout noise, alignment stabilities, and GRS stability using electronic readout only. Just as spacecraft attitude control system performance relies on simulations, so too the acquisition simulations represent the highest-fidelity tests of specific acquisition scenarios shy of flying the real hardware, and with the benefit that simulations can test the "edge cases" in a way that is not captured in any high-fidelity hardware test.

The link-acquisition problem for the Laser Ranging Interferometer (LRI) on GRACE Follow-On, described below, has only five degrees of freedom, but studies and simulations for that project delved to additional levels of fidelity of the influence of beam misalignments and phasemeter acquisition strategies that can be applied to the LISA case.

Technology development and validation not funded under this Technology Roadmap

LISA Pathfinder

No discussion of technology development for LISA would be complete without discussing LISA Pathfinder (LPF), which will demonstrate the Disturbance Reduction System (DRS), as discussed in Section 2.5.

GRS Torsion Pendulum

At the inception of LPF, it was believed that ground testing would not be able to reach LISA-like sensitivities for GRS performance. A torsion balance developed by the GRS developers at the University of Trento has achieved one-dimensional sensitivity approaching the LISA requirement and has been able to use this for extensive error budget checking for a representative electrode configuration but distinctly non-representative proof mass. For example, a class of surface force errors can be magnified by using a low-mass (hollow) proof mass as a more sensitive probe than a full GRS would provide. The GRS testbed work has been supported by the European Space Agency (ESA).

GRACE Follow-On Laser Ranging Interferometer

NASA's GRACE Follow-On Mission relies on measurement of the fluctuations in the separation between two spacecraft in a following polar Earth orbit to measure variability in Earth's gravity caused primarily by water redistribution. Scheduled to launch in 2017, in addition to the microwave measurement system flown on GRACE and adapted to the GRAIL mission to the Moon, GRACE-FO will carry an interspacecraft LRI to make identical measurements with nanometer precision. Based largely on interferometer technology development from LISA and component technology investments from Earth-science technology programs, the LRI functional elements and signal parameters largely match LISAs, as shown in Figure 3 and Table 2. While the measurement requirements for the LRI are 1000× less stringent than on LISA, the laser

frequency control requirements are more stringent and interferometer link acquisition relies on LISA levels of performance for component noise. The LRI represents significant risk reduction for LISA in interspacecraft interferometry, although the simple optical bench and “telescope” are not LISA-like.

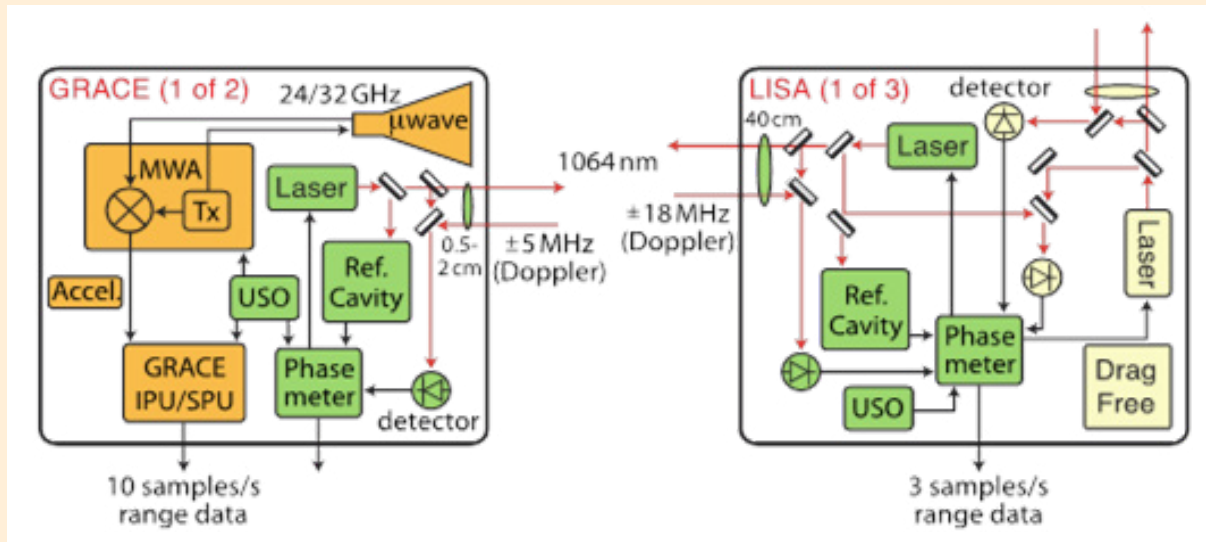


Figure 3: Laser readout and frequency control on the LRI on GRACE Follow-On is nearly identical to LISA.

Table 2— The LRI has similar signal parameters and functionality to LISA and relies on LISA technology development to date. LISA performance requirements are tighter than those of LRI (picometers instead of nanometers) with the exception of laser frequency noise, for which LRI has a tighter requirement.

Parameter	LRI	LISA
Measurement Noise	0.08 $\mu\text{Hz}^{-1/2}$	$2 \times 10^{-5} \mu\text{Hz}^{-1/2}$
<i>Shot Noise</i>	<i>0.01 nm/Hz^{1/2}</i>	<i>7 pm/Hz^{1/2}</i>
<i>Photoreceiver Noise (but note carrier to noise density requirement)</i>	<i>1 nm/Hz^{1/2}</i>	<i>3 pm/Hz^{1/2}</i>
<i>Phasemeter Noise</i>	<i>1 nm/Hz^{1/2}</i>	<i>1 pm/Hz^{1/2}</i>
<i>Optical Pathlength Noise</i>	<i>30 nm/Hz^{1/2}</i>	<i>3 pm/Hz^{1/2}</i>
<i>Laser Frequency Noise</i>	<i>35 nm/Hz^{1/2}</i>	<i>1 pm/Hz^{1/2}</i>
<i>USO Noise</i>	<i>1 nm/Hz^{1/2}</i>	<i>1 pm/Hz^{1/2}</i>
Satellite Separation	170..270 km	5 million km
Satellite Relative Velocity	$\leq \pm 3\text{m/s}$	$\leq \pm 15\text{m/s}$
Wavelength	$1.064 \times 10^{-6}\text{m}$	$1.064 \times 10^{-6}\text{m}$
Phase Precision	$10^{-3} \text{ cycles Hz}^{-1/2}$	1 microcycle $\text{Hz}^{-1/2}$
Nominal Carrier-to-noise Density	$\geq 75 \text{ dB-Hz}$ (single phasemeter channel)	$\geq 75 \text{ dB-Hz}$ (single phasemeter channel)
IF Signal Frequency	4–16 MHz	2–18 MHz
IF Signal Dynamics (@ 1 Hz)		
<i>Before Frequency Stabilization</i>	<i>5000 Hz $\text{Hz}^{-1/2}$</i>	<i>5000 Hz $\text{Hz}^{-1/2}$</i>
<i>After Frequency Stabilization</i>	<i>30 Hz $\text{Hz}^{-1/2}$</i>	<i>300 Hz $\text{Hz}^{-1/2}$</i>
Science Bandwidth	2 MHz–0.1 Hz	0.1 MHz–1 Hz
Rx Optical Power	79–625 pW	80 pW
Number of Phase Channels	4	44+
ADC Clocking Rate	38.656 MHz	50 Mhz
Time Coordination	GPS (laser ranging code could be used)	Laser ranging code
Laser Phase Locking	Required	Required
Pointing Information	Wavefront sensing	Wavefront sensing
<i>Pointing Precision</i>	<i>1 $\mu\text{rad}/\text{Hz}^{-1/2}$</i>	<i>80 nrad/Hz^{-1/2}</i>

Potential use of the LRI on GRACE-FO as further risk reduction for LISA

NASA's Astrophysics Research and Analysis (APRA) program has funded the development of experiments that could use the LRI on GRACE-FO as further risk reduction for LISA by performing in-flight tests of TDI and arm locking. The LISA Experience from GRACE-FO Optical Payload (LEGOP) [McKenzie: 2011] task does not cover implementation of flight experiments, but rather designs the experiments and proves their viability through simulation and ground testbed verification. LEGOP ends in FY15.

- Continuous measurement of range between S/C (to 8 ns accuracy)
- Lock laser on S/C 1 to cavity, let laser on S/C 2 be free running.
- Record dual one-way links—will be dominated by laser frequency noise. Send data to ground.
- In post-processing: Use measured range to combine dual one-way according to TDI. This will remove laser frequency noise, recovering performance set by pre-stabilization cavity.
- Phase-lock laser on S/C 2 to incoming laser (so that it looks like a mirror).
- Lock laser on S/C 1 to arm by locking to incoming light.
- Compare “arm-locked” frequency stability to cavity stability.

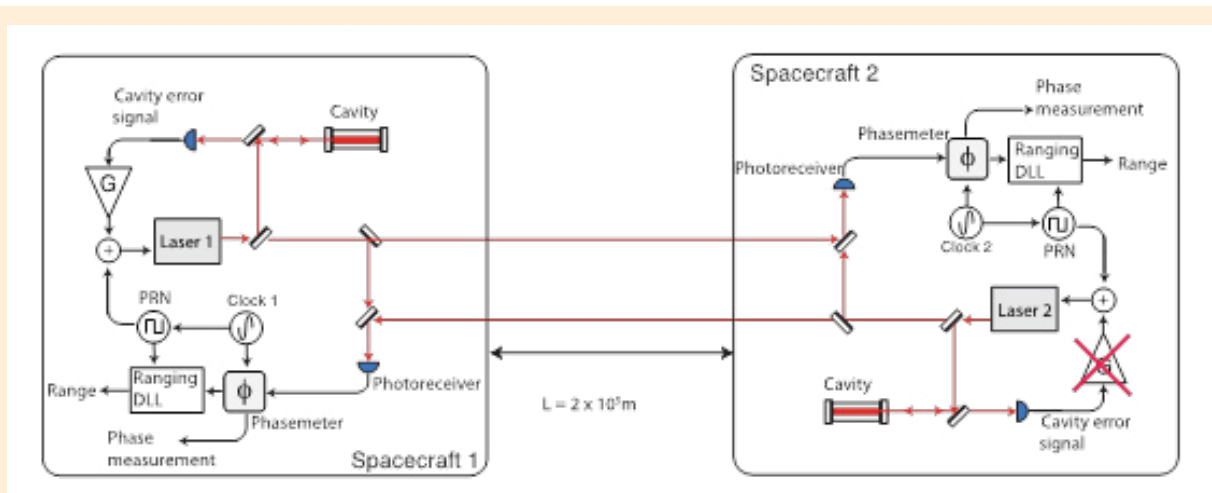


Figure 4: LEGOP proposed experiment to demonstrate Time Delay Interferometry on the LRI on GRACE-Follow On as risk reduction for LISA not covered by GRACE-FO directly or by LISA Pathfinder.

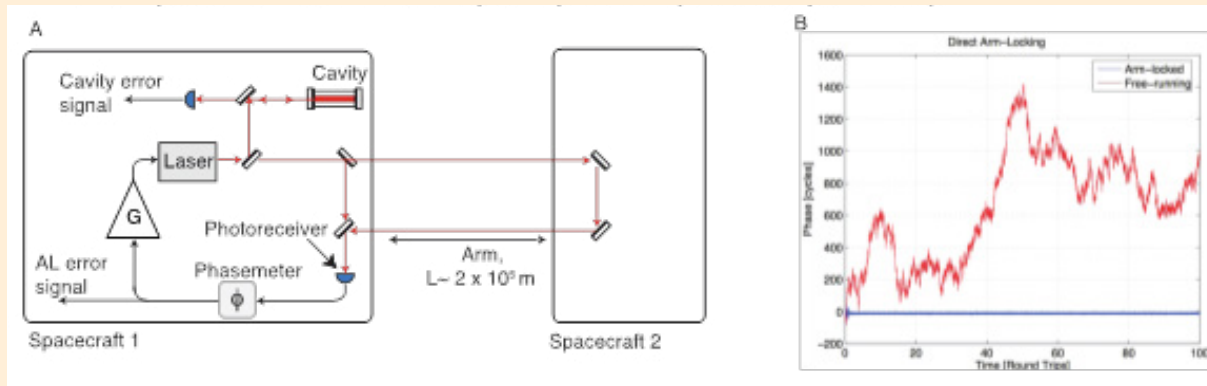


Figure 5: LEGOP proposed experiment to demonstrate arm locking on the LRI on GRACE-FO as risk reduction for LISA not covered by GRACE-FO directly or by LISA Pathfinder.

A flight demonstration of TDI and arm locking would require additional technology funding through the Physics of the Cosmos (PCOS) office and the approval of the GRACE Follow-On Project. LEGOP experiments are designed around the constraints of the planned LRI hardware and can be implemented through a firmware upload to the LRI post launch. This upload capability exists in the LRI hardware (the LEGOP team is directly involved in the development of the LRI on GRACE-FO). With a launch in 2017 and a 1-year LRI mission, flight versions of the LEGOP experiments could be performed in 2018 (estimated cost of \$1.4M in FY12 dollars).

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3 Cost and Schedule Summary

As noted previously (Section 1.5), the individual technology development efforts may be performed independently of one another. The cost and schedule estimates provided in Section 2 allow phasing of the various development tasks to fit within annual spending caps. It should be noted, however, that each technology plan was developed assuming no interruption in development for that technology.

Table 1 shows the cost and schedule summary for each technology for an ESA-led mission. Because the start year for a given development effort may vary to fit within limits, the table does not list a specific date, but rather shows the summary duration and costs for each technology. The table demonstrates that all technologies can be at TRL 5 by the required FY18 date, assuming all technology efforts begin in FY15.

Table 2 shows the cost and schedule summary for each technology for a NASA-led mission. As with the ESA-led mission, technologies may start at varying points in time. In Table 2, it is assumed that the four critical technologies (lasers, microthrusters, phasemeter, and telescopes) would begin development 2 years ahead of the key technologies (optical bench and GRS). This is based on assumed future cost constraints, and ensures the critical technologies are developed on a schedule that still supports potential selection for an ESA-led mission. The optical bench activity has been divided between the optical bench development and the associated testbed development for clarity. Table 2 demonstrates that all technologies can be at TRL 5 by the required FY20 date, assuming all optical bench development efforts begin in FY16 and GRS development efforts begin in FY17. If optical bench development does not begin until FY17, all technologies are still complete; however, final optical bench interferometer testbed testing will not be completed.

Table 1—Cost and Schedule Summary of an ESA-led Mission

ESA-led Mission	FY15		FY16		FY17		FY18		FY19	
	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)		
Lasers	1.8	800	0.9	180						
Microthrusters	5.6	1175	1.1	275	6	500	3	100	Costs continue at FY18 rate if thruster test extended	
Phasemeter	1.35	25	0.75	75						
Telescope	3	1800	2	2000						

Table 2—Cost and Schedule Summary of an NASA-led Mission

NASA-led Mission	FY15		FY16		FY17		FY18		FY19		FY20	
	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)	FTEs	Procurement (\$k)
Lasers	1.8	800	0.9	180								
Microthrusters	5.6	1175	1.1	275	6	500	3	100	Costs continue at FY18 rate if thruster test extended			
Phasemeter	1.35	25	0.75	75								
Telescope	5	1600	2	1700	1	1000						
Optical Bench			4	230	1	200	0.5	10				
Optical Bench Testbeds					3	400	3.5	700	2	300	1	300
GRS					2.75	270	2.5	10	2.5	10		

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Appendix B — Acronyms

APD	Astrophysics Division
ACS	Attitude Control Subsystem
ASE	Amplified Spontaneous Emission
CFRP	Carbon Fiber Reinforced Polymer
CMNT	Colloidal Micro-Newton Thrusters
COTR	Contracting Officer Technical Representative
CSS	Coarse Sun Sensor
CTE	Coefficient of Thermal Expansion
CW	Continuous Wave
CY	Calendar Year
DFB	Distributed Feedback
DBR	Distributed Bragg Reflector
DOF	Degrees of Freedom
DRS	Disturbance Reduction System
DSN	Deep Space Network
eLISA	evolved Laser Interferometer Space Antenna
ECL	External Cavity Laser
EOL	Laser Output Power
ESA	European Space Agency
FFT	Fast Fourier Transform
FTE	Full Time Equivalent
FY	Fiscal Year
GPS	Global Positioning System
GRS	Gravitational Reference Sensor
GSFC	Goddard Space Flight Center
GW	Gravitational Wave
HGA	High Gain Antenna
IMS	Interferometric Measurement System
ITT	Invitation To Tender
JPL	Jet Propulsion Laboratory
LISA	Laser Interferometer Space Antenna
LPF	LISA Pathfinder
LTP	LISA Technology Package
MOC	Mission Operations Center
MOPA	Master Oscillator Power Amplifier
NGO	New Gravitational-wave Observatory
NMP	New Millennium Program
NPRO	Non-Planar Ring Oscillator
NWNH	<i>New Worlds, New Horizons in Astronomy and Astrophysics</i>
PCOS	Physics of the Cosmos
PDR	Preliminary Design Review
PI	Principal Investigator
SBIR	Small Business Innovation Research
SBS	Stimulated Brillouin Scattering
SGO	Space-based Gravitational-wave Observatory
SGO Low	Space-based Gravitational-wave Observatory Low concept

SGO Mid	Mid-sized Space-based Gravitational-wave Observatory
SGO High	Space-based Gravitational-wave Observatory High concept
SODPC	Science Operations and Data Processing Center
ST7	Space Technology 7
TDI	Time Delay Interferometry
TDR	Technology Development Roadmap
TM	Test Mass
TMA	Three-Mirror Anastigmat
TMB	Technology Management Board
TRL	Technology Readiness Level
UV	Ultraviolet
YAG	Yttrium Aluminum Garnet