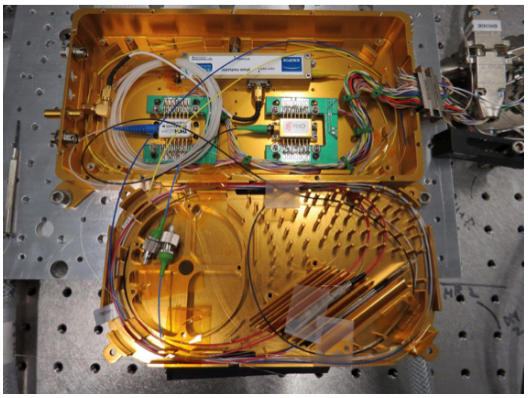
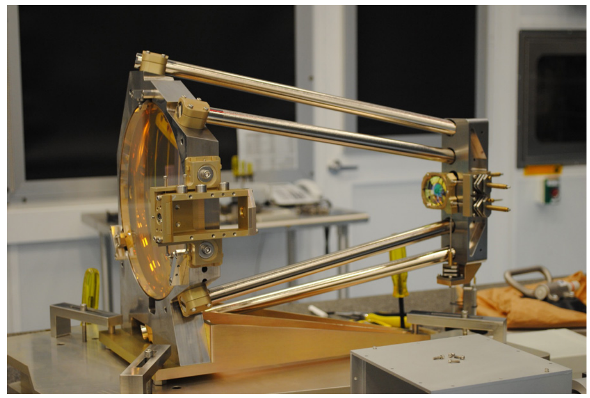
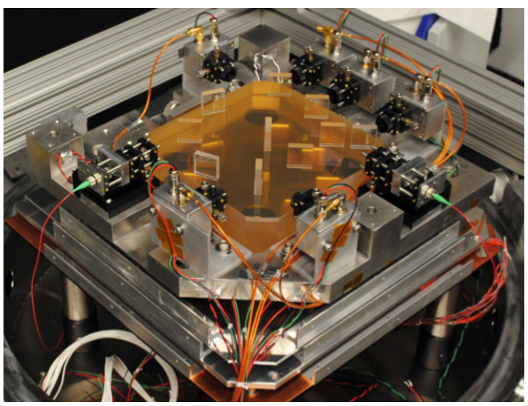
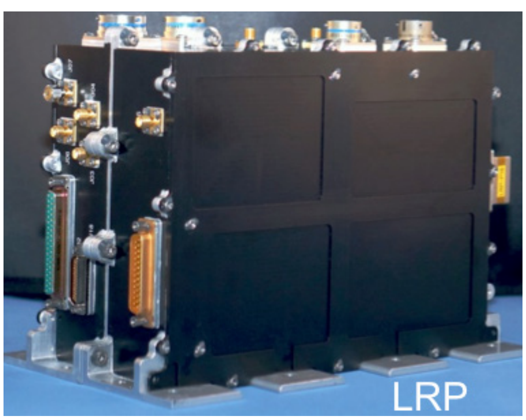
National Aeronautics and Space Administration

L3 Study Team Interim Report









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Executive Summary

The L3 Study Team (L3ST), with support of the Technology Assessment Group (TAG) and the Physics of the Cosmos (PCOS) Program study office, was charged as part of their Phase 1 activities to provide an analysis of potential US hardware contributions to the ESA-led L3 Gravitational Wave mission and an assessment of their consequences on cost, risk, and science return. In this interim report, we provide a preliminary assessment focusing on the major instrument subsystems that the US is best-positioned to provide. We expect and encourage that the establishment of roles and responsibilities will steadily evolve and that further input beyond what is contained in this report will be required.

In addition to our assessment of particular candidate contributions, we highlight the following general findings:

- *The science case for a space-based GW observatory, endorsed by both the 2010 Decadal Survey and ESA's 2013 Cosmic Visions process, remains compelling. Realizing a mission that fully delivers this science in a timely fashion and with low risk should be the primary objective of US participation in L3.*

- *The L3ST concurs with the ESA's GOAT report that meaningful participation of the US community in the design, development, and operation of L3 will result in a mission that is more technically robust and more scientifically capable.*

- *US contribution of central elements of the payload is an effective way to enable meaningful participation and provide impact on, and insight into, the final flight design.*

- *The US has strengths in a broad range of technologies relevant to L3. Opportunities should be sought to employ all of these strengths in the partnership regardless of the specific hardware items delivered.*

The L3ST and TAG considered five major instrument systems as potential US contributions to L3: the *laser system*, the *micropropulsion system*, the *optical bench*, the *phase measurement system*, and the *telescope*. For each potential contribution, we evaluated the delivery cost, the simplicity of integration, the relevant US capabilities, and most importantly the impact US involvement would have on the overall outcome of the mission. **Table 1** summarizes our analysis, which is discussed further in the main body of the report. For each potential contribution and evaluation criteria, the table lists relevant comments as well as a shading that indicates the relative merit in this criteria. Darker shading indicates stronger performance against a particular criterion.

A conclusion of our analysis is that multiple viable options of US participation in L3 exist, each with a different mix of cost, risk, and impact. While it is likely that the US will only contribute a subset of these items to the final partnership, continuing some level of development across the entire portfolio is an effective strategy to reduce overall mission risk as well as provide additional insight to the US science and technology communities.

In the remainder of this report, we briefly comment on the science case for a LISA-like mission and provide a further description of our technology analysis.

Table 1: Summary of L3ST's preliminary analysis of potential US contributions of major instrument systems to L3. For each evaluation criteria, darker shading indicates stronger performance against a specific criterion. While all criteria are important, the L3ST believes that 'Impact and Insight' will have the most influence on overall mission performance and risk. The 'Rough Delivery Cost' figures assume US approaches to costing, and may differ significantly from European estimates.

Major Instrument System	Impact and Insight	US Capabilities & Heritage	Implementation Simplicity	Rough Delivery Cost Estimate (FY16 M$)
Laser	Moderate coupling to science performance	Novel seed laser; transparent design	Simple instrument interfaces. Requirements moderately stable.	~60
Micropropulsion	Limited coupling to science performance	Flight demo on LPF No equivalent European system	Minimal interfaces with instrument. Additional interfaces with flight system	~90
Optical Bench	Core of physical measurement. Insight into other systems	Limited investment to date.	Many optical, mechanical, and thermal interfaces. Design less mature. Close coupling with telescope	~100
Phase Measurement	Core of instrument control & operation	Extensive LISA development Flight demo on GRACE-FO	Many electrical and control system interfaces	~70
Telescope	Significant impact on science performance	Moderate grant-funded development. Aligns well with core competencies	Several optical, mechanical, and thermal interfaces. Close coupling with optical bench	~90

Science and Data Analysis

One element of the L3 Study Team's charge is to identify mechanisms for US participation in a space-based gravitational wave mission that are responsive to the needs and priorities of the US astrophysics and relativity community. Establishing these needs and priorities is expected to evolve in the second phase of the L3ST study into the development of a strong science case for US participation in L3 that can be used as input to the 2020 US Decadal Survey. The L3ST has organized two working groups to support this effort, a Science Analysis working group and a Data Analysis working group. In this interim report, we briefly discuss some results from these groups.

The science case for a LISA-like observatory remains strong. The milliHertz band is expected to be a very fertile ground for gravitational wave astronomy (see **Figure 1**) and a space-based instrument is required to access it; in addition, a space-based instrument is the only known way to make precision measurements of gravitational-wave amplitudes. The high ranking received by the LISA project in the New Worlds, New Horizons report was in large part due to this strong science case. However, it is also important to note that the science case has and will continue to evolve as astrophysics theory and other fields of observational astronomy progress. This will help mature the L3 science case. Identifying and capitalizing on newly recognized science

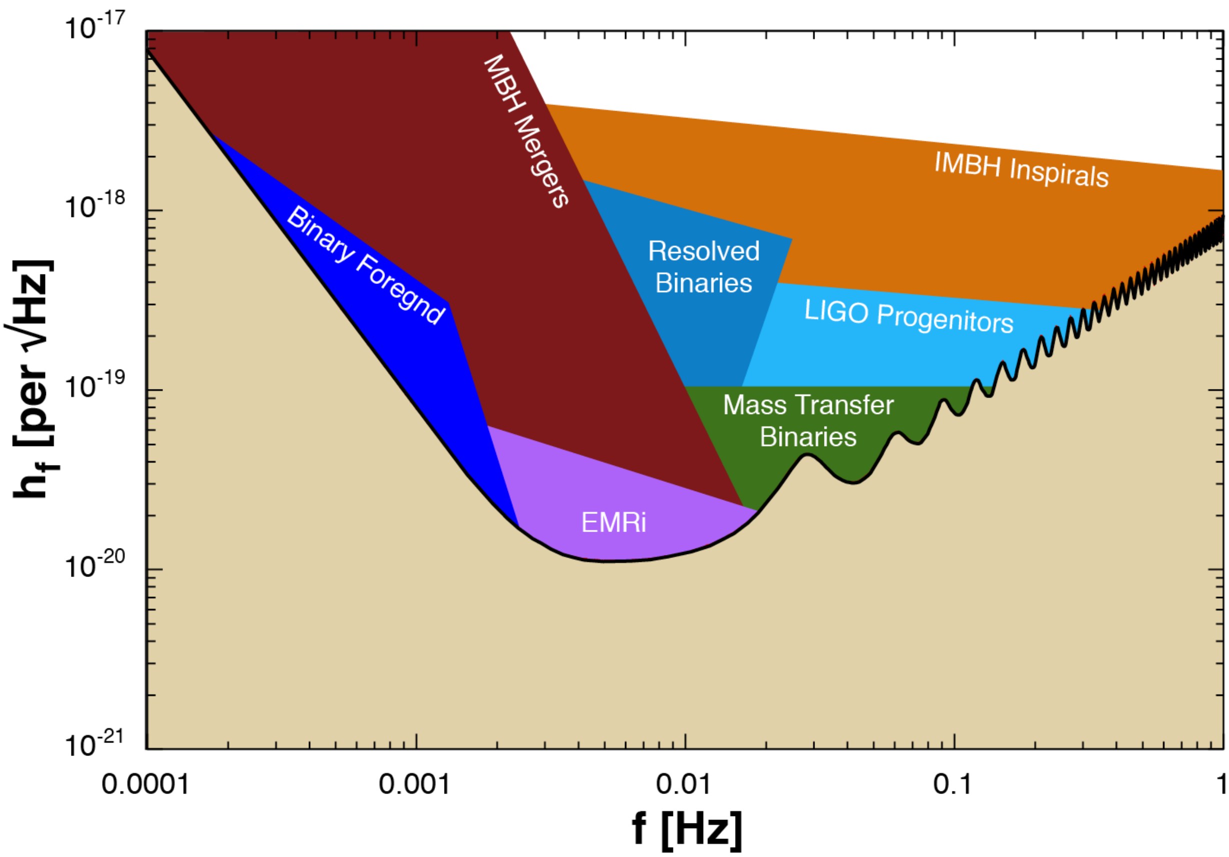

Figure 1: Discovery potential for a LISA-like mission. The area above the black curve represents the portion of the GW spectrum accessible to LISA, with the height above the line corresponding to SNR. The colored regions represent different astrophysical source populations.

targets in advance of the 2020 Decadal Survey will require increased effort on the part of the US research community and closer coordination with our European counterparts.

The most notable scientific event since the last major review of the LISA science case (2013's ESA Cosmic Visions L2/L3 selection process) was the first direct detection of astrophysical gravitational waves by the LIGO/VIRGO collaboration. The excitement generated by this achievement spread far past the gravitational wave community, making a significant impact on astronomers, the broader scientific community, and the public at large. It is also worth noting that GW150914 provided a scientific surprise in the form of the large masses of the black holes responsible for the event. This is a perfect illustration of the discovery potential associated with observing a truly unexplored sector of the universe. The subsequent announcement of a second black-hole merger (GW151226) by LIGO confirms that a population of such sources exists and clearly marks the transition to a new astronomy, with a space-based mission complementing LIGO as radio or x-ray astronomy does optical observations.

Technology Assessment

Mission Architecture and Development Assumptions

A thorough and accurate evaluation of technology readiness, development activities, and delivery costs necessarily relies on a well-defined and stable mission architecture. For the case of L3, such an architecture is not likely to be defined until after the ESA mission architecture studies currently expected to start in CY2017. For the purposes of this report, we adopt the baseline LISA architecture as defined in the 2011 ESA Yellow Book. We also note that this architecture is compatible with the recommendations in the final report of ESA's Gravitational Observatory Assessment Team (GOAT). **Table 2** below summarizes the relevant parameters.

Table 2: Assumed Mission Design Parameters

Parameter	Value
Arm length	5 Gm
Number of Links	6 (a.k.a 3 arms)
Acceleration Noise	3 $fm/s^2/Hz^{1/2}$ x $[1+(f/3mHz)^4]^{1/2}$
Position Noise	12 $pm/Hz^{1/2}$ x $[1+(3mHz/f)^4]^{1/2}$
Telescope Diameter	40cm
Laser Power [derived]	2.0W
Mission Lifetime	5 years minimum
Measurement bandwidth	0.1mHz zto 1 Hz

The overall readiness of the LISA concept has been significantly reinforced by the results from the ESA-led LISA Pathfinder (LPF) mission. The preliminary result from the European LISA Technology Package demonstrated an acceleration noise that far exceeded the requirements set for LPF and approaches the value in **Table 2**. This is an important validation of several individual technologies as well as the overall approach. The NASA-provided Disturbance Reduction System payload on LPF, which consists of a micropropulsion system and a dynamic control system, is currently scheduled for commissioning activities in late June 2016 and will conduct science operations for several months afterwards. During these operations, the US and European payloads will effectively operate as a single instrument much as would be required for L3.

Contribution Categories

Our analysis concludes that several viable options exist for the US to play a substantive role in an ESA-led L3 mission. These options have been broken into the categories described below. Note that these categories are not mutually exclusive; potential partnership scenarios may involve elements from more than one category.

Category I: Major Instrument Systems

Major instrument systems for which the function and interfaces with the larger payload are reasonably-well defined. These represent the most likely major direct US contributions of flight hardware to ESA's L3 mission. The L3ST analysis is based on the breakdown to six major instrument systems of the LISA science instrument. These major instrument systems are the *Gravitational Reference Sensor*, the *Laser System*, the *Micropropulsion System*, the *Optical Bench*, the *Phase Measurement System*, and the *Telescope Assembly*. Based on the recently-reported spectacular success of LISA Pathfinder, which flew a Gravitational Reference Sensor largely identical to that envisaged for LISA, the L3ST does not consider US delivery of a Gravitational Reference Sensor for L3 a likely outcome and did not consider such a scenario in this report. The remaining five major instrument systems were each considered as potential US contributions.

Category II: Components or instrument subsystems

A second way in which the US might materially contribute would be the development and delivery of components or subsystems to a major instrument subsystem that is delivered by ESA or a European Member State. This might involve items for which the US has some unique capability or experience such as photoreceivers for the optical bench, a UV discharge system for the Gravitational Reference Sensor, or elements of the phase measurement system. This mode of participation would require, and thus enable, US insight into the relevant payload subsystem with benefits to operations and science data analysis. This may also provide a mechanism to offset costs at the member state level, easing the negotiations to a mutually agreeable partnership. A detailed inventory and analysis of these contributions is beyond the scope of this interim report, but will be considered by the L3ST in the future.

Category III: Off-the-shelf items offering limited technical insight

Colloquially referred to as "non-noble work", these items require no technology development and little immediate system engineering activities. Examples include standard spacecraft components and subsystems (star trackers, propulsion modules, etc.) and operations support. These contributions may be essential to enable the mission, but should be balanced with work that yields more technical engagement and insight into the mission design. As the rationale for selecting these items is not likely to be technical, we do not assess specific contributions in this report.

Category IV: Mission design

The range of relevant expertise in the US exceeds the likely scope of hardware contributions available as a minority partner. Engaging the US technical community in the design and development of the mission concept can leverage this expertise and reduce the overall mission risk. Such participation could be facilitated by selecting hardware contributions that are tightly connected to the overall mission design.

Cost context

Unlike most early-stage studies, the L3ST has the benefit of a wealth of extremely detailed material produced by earlier efforts to develop space-based gravitational wave interferometers. Most notable is the joint NASA/ESA Laser Interferometer Space Antenna (LISA) project, which ran from 2001 through 2011. Numerous costings of various types (independent and internal, grass-roots and parametric) of the LISA concept were made in the 1990s and 2000s. None of those costings assumed an L3-like partnership with European leadership and the US as a minority partner. However, they are nonetheless useful for providing context of the relative costs of major components of the mission. **Table 3** summarizes one such estimate for the overall mission cost, made by JPL's Team-X in 2011. The values have been converted from their original $FY12 basis to $FY16.

It is illustrative to compare these numbers in the context of the cap for US hardware contributions of $150M that was identified in the L3ST charter. Considering two extremes, this amount could either be spent entirely on non-noble work (disposable propulsion modules) or could provide roughly a third of the total science instrument complement.

Table 3: Rough cost breakdown estimate for LISA project from 2011 Team-X study of the SGO-High concept, which was architecturally similar to the LISA concept of the 2010 Decadal. The cost estimates have been updated to FY2016 from FY2012 estimates using standard assumptions. These figures assume US approaches to costing, and may differ significantly from European estimates.

Item	Cost (FY2016 $)	Comments
Sciencecraft (3)	$372M	Phase A-D WBS element 6 (bus)
Prop Module (3)	$164M	Phase A-D WBS element 6
Payload ("science complement") (3)	$448M	Phase A-D WBS element 5 (instrument)
Launch Vehicle	$257M	Atlas V
Management & Mission Assurance	$74M	Phase A-E ($61M is just Phase A-D)
Systems Engineering & Integration	$113M	Phase A-D
Operations	$219M	Phases E-F: Includes Mission Design, Mission Ops, and Ground Data systems
Science	$107M	Phases A-F: Includes EPO
Explicit Reserves	$440M	$394M Phase A-D, $46M Phase E-F
Total	**$2.2B**	

Both the parametric and grass-roots costing models can also be used to produce estimates for the delivery costs of the major instrument subsystems. These delivery cost estimates provided in **Table 1** were drawn from cost estimates developed by the LISA project and a Team-X review in advance of the 2010 Decadal Survey.

Development costs

Development costs are likely to drive the financial burden of US participation in L3 in the near term and as such are an important consideration. Estimating hardware development costs at this time is challenging for several reasons. The uncertainties in the mission architecture, and in particular the development schedule, lead to large uncertainties in the development cost. For example, a prominent feature of ESA's development strategy for L3, as outlined in the GOAT report, is the inclusion of a Payload Engineering Model (PEM) Phase. The purpose of this phase is to identify and retire system-level risks early in the process by bringing together various subsystems of the full instrument. If ESA adheres to this plan, and the US contributes a major subsystem or component to the payload, this will imply participation in this activity and associated costs. However the scope, objectives, and timeline for the PEM phase are not sufficiently well defined at this time.

Understanding, and contributing to, the technology development strategy for L3 is a prime example of the advantages of engaging the US technical community with their European counterparts early in the mission development process.

Assessment Process

Technology Working Group developed a set of ten metrics for use in assessing the relative merits of the various potential contributions. These metrics are:

1. *Insight into System Performance*
   Would a US contribution of this element give US scientists an opportunity to influence the overall science performance of the gravitational-wave instrument?

2. *Insight into System Design*
   Would a US contribution of this element give US scientists deep insight into the design of a gravitational-wave instrument with the associated benefits to downstream science analysis and future missions utilizing related technologies?

3. *Prior NASA Investment*
   Have significant investments been made on this technology by NASA in the past, either as part of the LPF or LISA projects or as part of another effort?

4. *Uniqueness of NASA Offering*
   To what extent does the technology available in the US differ from its European counterpart and what potential advantages does it bring?

5. *Flight Experience*
   Does the US have flight experience with this particular type of hardware contribution?

6. *Technical Readiness*
   What is the current state of readiness for this technology in the US?

7. *Maturity relative to European counterpart*
   How does the readiness of the US version of this technology compare with the European one?

8. *Previous Partnership Experience*
   Is there precedent for US successfully contributing hardware of this kind to a European mission?

9. *Clean Interfaces*
   Are the hardware interfaces for this contribution known and well-defined? How many other systems does this contribution interface with?

10. *Stable Interfaces*
   How likely are the interfaces between this and other systems likely to change?

The Technology working group conducted an informal survey of the L3ST and TAG members that consisted of scoring each potential contribution against ten metrics related to the evaluation criteria. For each criterion, each respondent was asked to provide a score of 1-4 with 1 being most favorable and 4 being least favorable. **Table 4** summarizes the result of the survey.

Table 4: Summary of technology assessment survey conducted by the technology working group. Each of the survey's respondents were asked to score each potential contribution against the criteria listed above on a scale of 1 to 4 with 1 being most favorable and 4 being least favorable. The values reported here represent the average score among the respondents. The criteria are grouped by categories that indicate which of the Table 1 criteria they influenced.

Criteria	Laser	Phasemeter	Telescope	Thruster	Optical Bench
Insight & Impact					
Insight into Performance	3	1	2	3	2
Insight into Design	3	2	2	3	1
US Capabilities & Heritage					
Prior NASA investment	4	1	3	1	4
Uniqueness of NASA offering	3	3	3	1	3
Flight Experience	3	1	3	1	4
Technical Readiness	3	2	3	1	4
Maturity relative to European Partner	3	2	2	2	4
Integration Simplicity					
Previous Partnership Experience	3	1	3	1	4
Clean Interfaces	1	2	2	1	3
Stable Interfaces	2	2	3	1	4

Assessment Summary

From the survey results and subsequent discussions, the Technology Working group developed a set of more general criteria that capture the most relevant aspects of any potential US contribution. These are the elements that are used in the overall summary presented in **Table 1**. The correspondence between specific survey criteria and the general criteria that they informed is indicated by the groupings in **Table 4**. The general criteria are:

Impact on and Insight into Mission Design

The biggest impact that the US can have in reducing the risk and enhancing the scientific capabilities of the mission is through its significant expertise in relevant technologies and institutional capabilities in spacecraft systems engineering. Realizing this impact requires participation by US scientists in the design, development, and operation of the mission. A specific US hardware contribution that is deeply connected with the whole of the instrument may facilitate such participation. US involvement in such activities would have the added benefit of providing insight and experience that can be applied to the eventual analysis of science data as well as to the design of future instruments for both gravitational wave detection and other applications.

US Capabilities and Heritage

The current level of readiness will affect both the development costs and development risks to NASA and is an important consideration. The L3ST believes that US scientists and industry are in principle capable of producing any part of the L3 flight system. However, the current level of US readiness is strongly influenced by prior investment and varies amongst the five major instrument systems under consideration. It is also worth noting that while the distributed nature of the gravitational-wave instrument limits the influence any one system can have on the overall measurement performance, some US contributions may offer unique technical or programmatic advantages over their European counterparts.

Simplicity and Stability of Requirements

US hardware contributions for which the interfaces are relatively well known, simple, and expected to remain stable reduce the risk of cost growth in the US. Previous experience providing similar hardware systems to other European-US partnerships also reduces some programmatic risks. However, it is worth noting that the European development strategy dictates that the instrument is distributed amongst many member states and (potentially) international partners. The overall risk to the mission associated with these interfaces is not necessarily reduced by the US supplying an item with “clean” interfaces.

In summary, there are a number of viable avenues by which the US can participate in an ESA-led gravitational wave mission with contributions that may increase scientific capability and reduce risk. The L3ST enthusiastically encourages NASA to pursue this partnership and the tremendously exciting science that it enables.

Major Instrument System Summaries

In the remainder of this report, we provide summaries of each of the major instrument systems considered by the L3ST. For each system, we describe the function, history and status of US development, potential partnership scenarios, and the development activities needed to prepare for flight.

Laser System

Overview

The laser system provides the light that is used to make the primary science measurement: the differential acceleration of two test masses on separate spacecraft. The main requirements, an example of which are shown in **Table 5** are high power, intensity stability, frequency stability, and the ability to inject phase modulation tones with low differential phase noise. In addition, the system must be sufficiently robust to maintain these requirements over the mission lifetime. The most likely architecture for realizing such a system is a master oscillator power amplifier (MOPA) design, which consists of a stable seed laser, a phase modulator, and a power amplifier.

Table 5: Notional laser system requirements, based on proposed designs from eLISA consortium

Power (W)	λ (nm)	Intensity Noise ($/Hz^{1/2}$) at 10^{-3} Hz	Intensity Noise ($/Hz^{1/2}$) at 10^{7} Hz	Frequency Noise ($Hz/Hz^{1/2}$) at 10^{-2} Hz	Frequency Noise ($Hz/Hz^{1/2}$) 1Hz ~ 1MHz	Differential Phase Noise ($rad/Hz^{1/2}$) at 10^{-2} Hz	Lifetime (years)
1.5	1064	10^{-4}	10^{-8}	300	~3e4 * (1/f) [TBC]	$6x10^{-4}$	2.5 [TBC]

Development efforts at Goddard have focused on a novel laser seed based on an External Cavity Laser (ECL), which offers some advantages over the more common non-planar ring oscillator (NPRO) designs. The Goddard laser system consists of a low-noise ECL oscillator and pre-amp, followed by a fiber power amplifier (**Figure 2**).

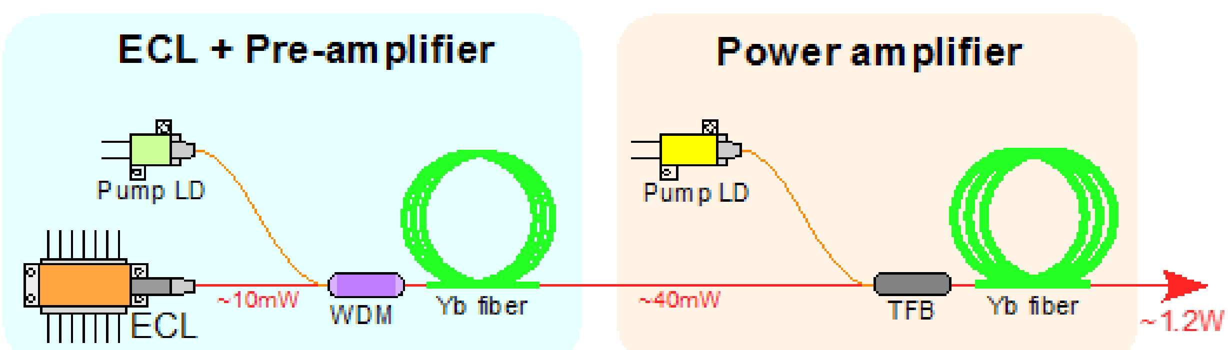

Figure 2: Block diagram of laser system under development at GSFC

The ECL (shown embedded in current driver in **Figure 3**) is a low mass, low cost, compact, simple, and highly reliable semiconductor laser, provided by a US vendor, Redfern Integrated Optics (RIO)1. It is comprised of a 400 µm size laser gain chip, integrated to a Bragg reflector etched into a planar silicon waveguide. A high reflectance coating applied to the gain chip together with the Bragg reflector forms an optical cavity. The pre-amp (shown in **Figure 3**, including phase modulator, pump diode and gain fiber) is a simple and highly reliable subsystem that amplifies the ECL output by a factor of 10.

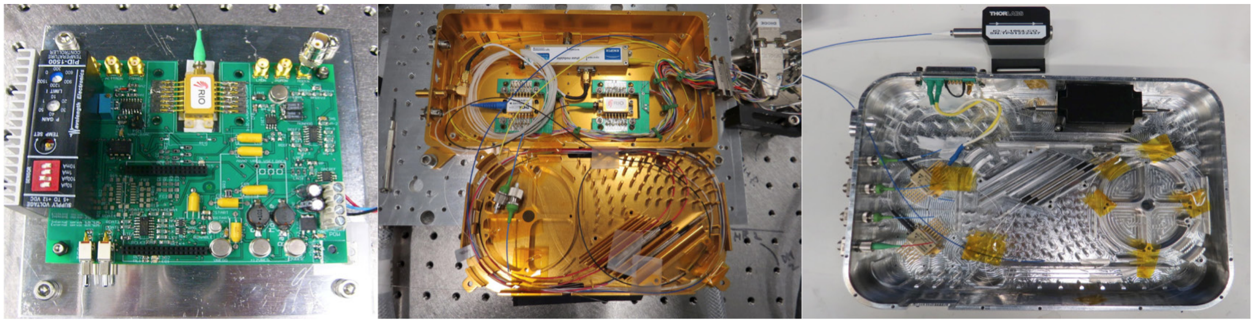

Figure 3: Major components of GSFC laser system. Left to right: ECL seed, pre-amplifier, and power amplifier.

For the amplifier, a laser design utilizing optical fibers presents many advantages over solid state bulk crystals, including: insensitivity to contamination problems and ease of alignment, since the light is maintained within the fiber core and waveguide; conveniently redundant design, since higher risk components such as pump diodes are easily made redundant by splicing them into the gain fiber; and leverage from the large resources of the fiber telecommunications industry. The amplifier is shown in **Figure 3** (with redundant pump diode and gain fiber).

Current Status

The full laser system (ECL, preamp, and amplifier) has been tested for noise and reliability. The current status is:

- Most of the requirements of **Table 5**, including power, amplitude noise, in-band frequency noise, and differential phase noise, are satisfied.
- The above-band frequency noise requirement needs to be verified and validated.
- The ECL and preamp meet basic environmental reliability tests, including vacuum thermal cycling, vibration, and radiation. (The amplifier has not yet been tested for reliability.)
- The ECL is undergoing a design modification to give the lowest possible phase noise. This is not yet complete.

Major Activities to reach PDR

The following activities are now underway to reach PDR. We estimate completion in 3 years.

- Completion of redesign of ECL parameters to minimize phase noise and the possibility of cycle slips during phasemeter operation. The redesign involves changes to the optical cavity spot size and reflectivity, and also the coupling to the gain chip. The phase noise requirement at high frequency depends on the light power level and the shape of the noise spectrum. We estimate that a factor of 3-5 reduction in phase noise is achievable, and will be sufficient. We are also building a space-qualified NPRO as a backup option.

- Amplifier environmental testing, including vacuum thermal cycling, vibration, and radiation exposure.
- Accelerated aging tests of laser system to verify laser lifetime.
- Long-term monitoring of laser system to verify stability.
- Implementation of ECL intra-cavity frequency modulator, allowing ~1 GHz actuation bandwidth. This will simplify the frequency stabilization system by eliminating the need for a separate component phase modulator.

Micropropulsion System

Overview

Colloid Micronewton Thrusters (CMNTs) provide low-noise, precise attitude control and drag-free operation of the spacecraft against disturbances, mainly solar pressure, that is required to measure gravitational waves. The thrusters produce a finely controlled electrospray (electrostatically accelerated charged droplets) using an ionic liquid propellant producing between 5-30 micronewtons of thrust with 100 nanonewton resolution. Busek Co., Inc. has worked with JPL to provide two 4-thruster clusters for the NASA Space Technology 7 Disturbance Reduction System (ST7-DRS) mission in 2008. ST7-DRS has been launched on board the ESA LISA Pathfinder Spacecraft and passed through its first commissioning check-out in January of 2016. All eight thrusters demonstrated full thrust range on orbit after 7 years of storage, fully loaded with propellant and no redundant parts (single-string). The thrusters will be used for science operations starting in July of 2016.

Figure 4: Colloidal Micro Newton Thruster unit on LISA Pathfinder

Current Status

The CMNTs for ST7-DRS and LISA Pathfinder have lifetime qualification tests and propellant tanks that are based on 90 days of operation for a technology demonstration mission. With the recent on-orbit experience of LISA Pathfinder, the thrusters are currently at TRL 7. No new technology development is required to design, build, and qualify colloid thrusters for a gravitational wave observatory. Since delivery in 2008, work has focused on developing a new, larger and fully redundant feed system for a 5-year flagship-class mission (currently at TRL 5 after NASA technology funding from 2013-2015) and physics based lifetime models. The models estimate 40,000 hours of useful life for the ST7-DRS design; however, there is still a large degree of uncertainty that requires longer duration tests for validation. To improve lifetime, thrust range, and lessons learned from the ST7-DRS and LISA Pathfinder experience, the thruster head and electrodes used to create the electrospray can be further optimized in terms aperture size and gap distances. The latest thruster design tools are based on the lifetime models, which have been validated by a series of 3000 hour class tests and full-life accelerated tests. Engineering development to TRL 6 based on architecture-level requirements along with long-duration testing is straightforward with little residual development or system risk. Additional long-duration tests were the next activity planned for the LISA Technology Development program before it was cancelled.

Major Activities to Reach PDR

To reach PDR, the architecture of the gravitational wave observatory, including the number and size of spacecraft, must be known along with thrust range requirements for tip-off recovery, science operations, and station keeping maneuvers. Assuming three spacecraft and a 5-year lifetime with similar thrust requirements from previous LISA studies, 6 active and 6 redundant thrusters will be necessary for each spacecraft. The configuration of the thrusters will depend on the specific spacecraft design parameters and requirements, but we expect that the primary and redundant thrusters will use the same propellant tank, which can be sized for an even longer 10-year mission. With 4 thrusters per assembly and 3 assemblies per spacecraft (all with only sun-opposing thrusters), the colloid subsystem, including control electronics and power processing units, would be very similar to the 4-thruster cluster units delivered on ST7-DRS. After receiving the propulsion system requirements, the following activities will bring the thrusters to TRL 6 in preparation for PDR.

- Finalize and test feed system and thruster head designs at prototype (TRL 5) level
- Subsystem / Assembly level design, packaging, and interface specification
- Fabrication of two Engineering Model / Qualification Model units
- Performance testing at the thruster unit level
- Environmental (vibration, thermal, etc.) testing at the full subsystem level
- Initiation of long duration tests, reaching at least 50% of design life by PDR and 150% of design life requirement by CDR (CDR requirements may drive schedule)

Since the architecture and full system requirements are not yet known, additional activities in preparation for expected requirements can commence now before a full system study is complete (expected to occur early in CY2017). Although no thruster units are expected to be required for the ESA Payload Engineering Model (PEM) phase, some low-level work during this early timeframe would allow significant progress on thruster design and feed system components. In addition, now that ST7-DRS has launched, two flight-spare thruster heads along with EM-level electronics and the TRL 5 fully redundant feed system are available for long-duration tests that could help validate lifetime models.

Key Considerations

ESA and one of its largest contractors, Airbus, are already familiar with the colloid thruster technology from development through operations. *ESA's software-based control laws have already been used to command the LPF colloid thrusters on-orbit*. Furthermore, the US team has worked with ESA well and understands their somewhat different review and documentation standards compared with NASA's standard practices. Since the interface to the thrusters is rather simple (standard spacecraft bus power and communications along with a simple mechanical mounting interface that requires minimal alignment constraints), the system is more robust to changing architecture-level designs that can drive cost increases in early mission phases. Finally, and perhaps most importantly, all of the technology challenges and much of the engineering development have all been completed on ST7-DRS and LISA Pathfinder. The contractor, Busek

Co., Inc, has continued to be engaged and funded by other NASA and DoD programs in this area, allowing them to continue to support future gravitational wave observatory studies and engineering model development. Together, all these factors form a strong basis of estimate and understanding of the work that would be required for an on-time, on-budget contribution.

Initially, since the thrusters do not have to participate in ESA's PEM phase, a low-level of funding can be used to help flesh out the TRL 5 system-level design and use flight-spare hardware from ST7-DRS for accelerated long-duration tests and further lifetime model validation. Once the propulsion requirements are set by an ESA-led system-level design study, engineering model development can begin in time for lifetime qualification tests to be completed by CDR with performance and environmental tests completed by PDR.

Partnership Description

The JPL-led thruster development team from ST7-DRS has already worked well with ESA and its contractors. Minimal participation in ESA's concept studies, including briefing teams or contractors with up-to-date status on the colloid thruster technology would lead to well-thought out requirements that drive further engineering development in the US. JPL would continue to work with Busek and other feed system component suppliers to integrate the thruster subassembly and provide a continual interface with ESA through PDR, CDR, and flight unit delivery and integration.

Optical Bench

The optical bench for LPF was very successfully designed, tested, and constructed by the University of Glasgow and their partners. For L3, the same core team is planning to use a similar manufacturing technique, based on hydroxy catalysis bonding of individual optical components to a monolithic optical bench. This bonding technique was originally developed and qualified for flight during the construction of telescopes used in the Gravity Probe-B mission. The Glasgow group has made significant progress in adapting the technique to build much more complex optical structures, culminating in the LISA Pathfinder optical bench.

While there are important advantages to keeping the design as close as possible to the LPF design, the LISA optical bench will be larger and have a substantially larger number of optical components on it. In addition, there will be six flight units plus a similar number of engineering models and spares to be manufactured.

The timely manufacturability of the OB (Optical Bench) was raised by the GOAT Report as one of the main schedule risks of a LISA-like mission. The Glasgow group and their industrial partners are actively working to address these risks by developing efficiencies in the manufacturing process. Activities in the US have been at a far lower level, with a handful of small, non-flight benches built in US research laboratories and the application of the hydroxy-catalysis bonding technique in at least one flight instrument (PIL lens assembly on JWST's NIRCam). If an opportunity can be found to utilize this experience or US industrial capacity in a collaborative manner that is beneficial to all parties, it may be an effective way to reduce the risk identified in the GOAT report.

An alternative approach to US involvement in the Optical Bench is through parallel design studies. The success of the LPF optical bench naturally leads to the desire to change as little as possible for the L3 system. However, the fact that the measured performance significantly exceeded requirements raises the possibility of tweaking the optical bench design to trade some of this performance margin for savings in other areas, such as ease of manufacture. An expansion of the one study of this kind now under way in the US to include support from engineers with experience in mechanical mounting technologies in space missions has the potential to reduce technical, programmatic, and schedule risk for the mission considerably. In addition, developing US insight in these technologies could benefit other areas of interest to NASA.

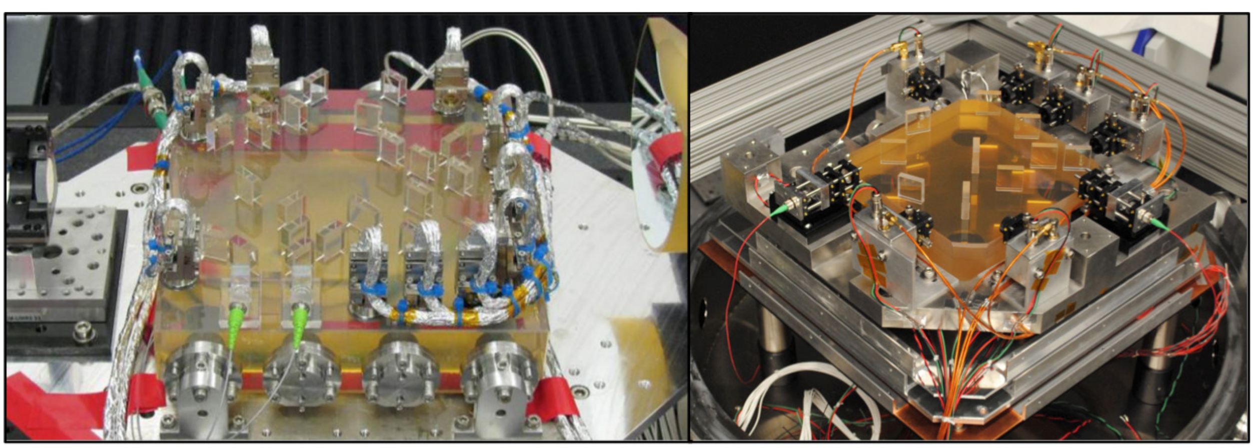

Figure 5: The flight optical bench for LISA Pathfinder (left) was successfully developed and delivered by the University of Glasgow and contributed to that mission's spectacular success. Activities in the US have been far more limited. One example is the design and construction of a non-flight, laboratory-scale optical bench including a stabilization cavity completed under GSFC internal funds (right).

Phase Measurement System

Overview

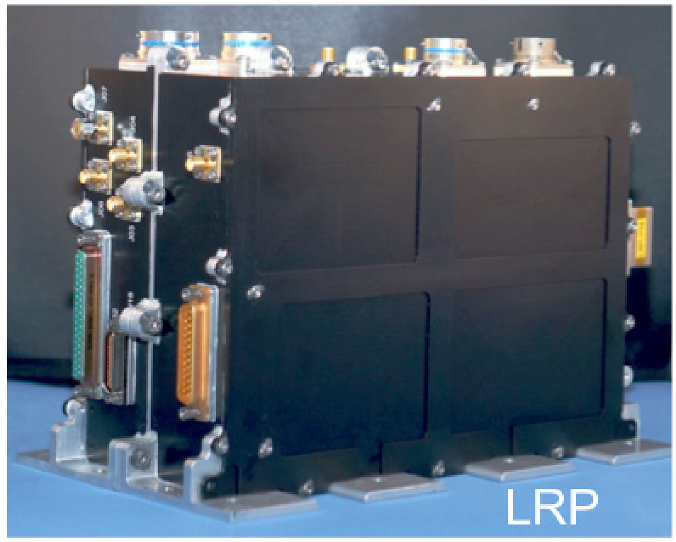

Figure 6: NASA/JPL delivered the flight Laser Ranging Processor unit for the Laser Ranging Instrument on GRACE-FO

The phasemeter provides the primary interferometric science readout in a LISA-like interferometer. A NASA phasemeter on L3 will be next in a line of successful phase tracking instruments for flight missions including the BlackJack family of GPS receivers flying on many Earth science missions, the GRACE and GRACE Follow-On missions, and on the GRAIL mission to the Moon.

NASA has been investing in the phasemeter for the LISA mission for more than a decade. The phasemeter was a NASA deliverable during the joint ESA/NASA LISA mission. More recently, NASA has delivered a flight phasemeter for the first inter-spacecraft laser interferometer, the Laser Ranging Interferometer (LRI) on GRACE Follow-On, scheduled to launch in 2017 (see **Figure 6**). The phasemeter for the LRI was derived from technology development for LISA and its flight heritage is directly relevant to LISA-like missions. The LRI is a US/German partnership, with the LRI instrument developed by the LISA interferometry experts on both sides of the Atlantic.

The driving phasemeter requirement is to make an accurate measurement of the phase of the interferometric beat-note between pairs of laser beams, both for the inter-spacecraft and local interferometry. LISA-specific challenges include microcycle/√Hz phase precision in the presence of large laser frequency fluctuations and a low SNR environment, and tracking the large and changing Doppler shift over the frequency range of 4-18 MHz. The primary science phase measurements are to be provided in a low-pass filtered version allowing representation at 3Hz sampling rate while representing a 1 Hz useful bandwidth. The “phasemeter“ performs many additional functions:

1. Phase-locks the slave laser to the received laser light
2. Stabilizes the master laser to the frequency reference (cavity)
3. Derives differential wave-front sensing signals for laser pointing
    a. *Implemented with a steering mirror on GRACE-FO*
    b. *Used for spacecraft pointing on LISA*
4. Measures “clock sidebands” for USO noise cancellation

5. Measures inter-spacecraft timing offsets to 3.3 nanoseconds absolute accuracy to facilitate Time Delay Interferometry

All above functions have been demonstrated at TRL 4/5 or above for LISA required levels. Items 1,2,3, and 4 have been developed for flight for the Laser Ranging Interferometer on the GRACE Follow-On mission. In addition the LRI carries a flight laser stabilization reference that meets the LISA requirements.

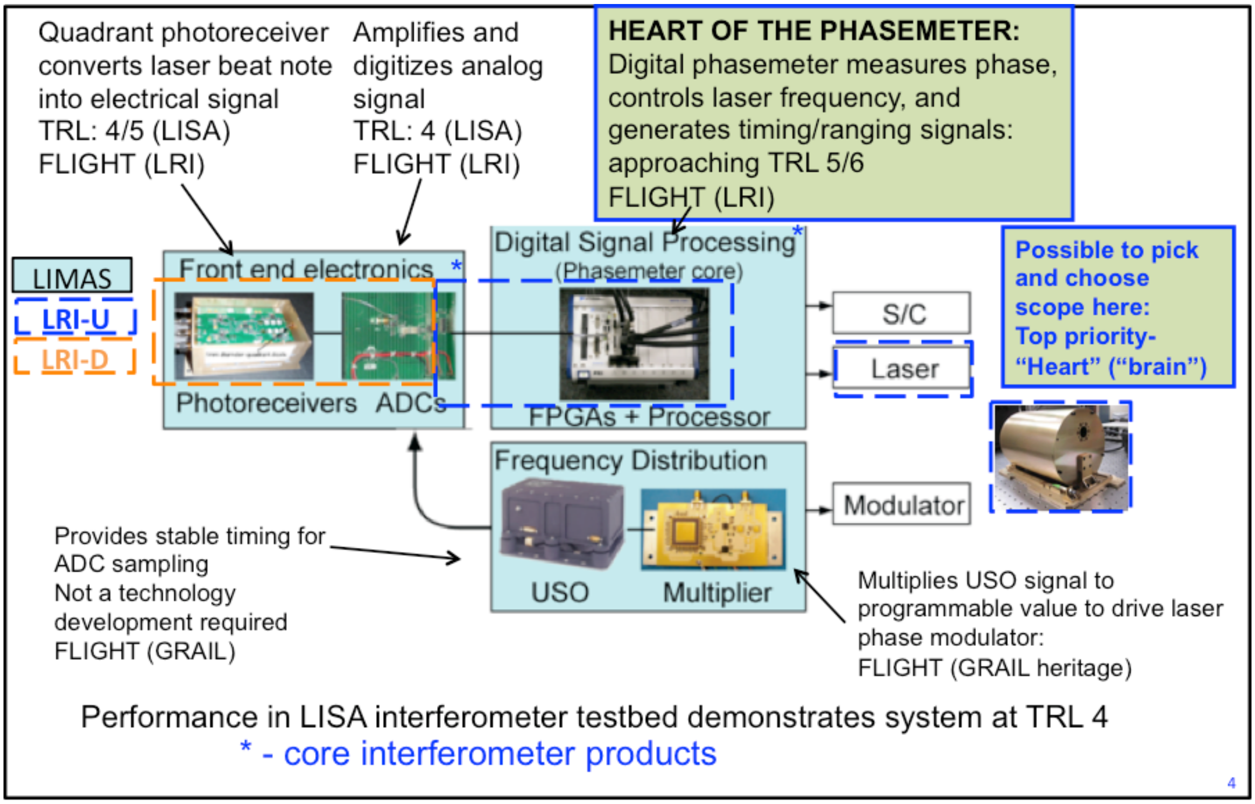

Figure 7: The "Phasemeter" digitizes signals from the photoreceivers and measures the resulting signal as the primary science observable. It also uses these inputs to control the laser frequency. The boxes shaded in blue are all parts of the "LIMAS" (LISA Instrument Metrology and Avionics System), part of NASA's contribution to the former LISA mission

In addition to the core Digital Signal Processing electronics and control algorithms the "Phasemeter" is sometimes taken to include all elements shown in the blue-shaded boxes in **Figure 7**. These blue shaded boxes were part of NASA's contribution to the former LISA mission, called "LIMAS" (LISA Instrument Metrology and Avionics System). The USO and Frequency Multiplier are already (TRL>6) flight items with heritage from the GRAIL mission. These represent examples of the 'Category II' contributions that the US could make to the phasemeter effort should it not be responsible for delivering the complete flight system.

Interfaces and block diagram

Phasemeter core interfaces from GRACE-FO are shown in **Figure 4**. These interfaces have been developed to flight for GRACE-FO and are expected to be identical on L3 with the exceptions noted in the caption.

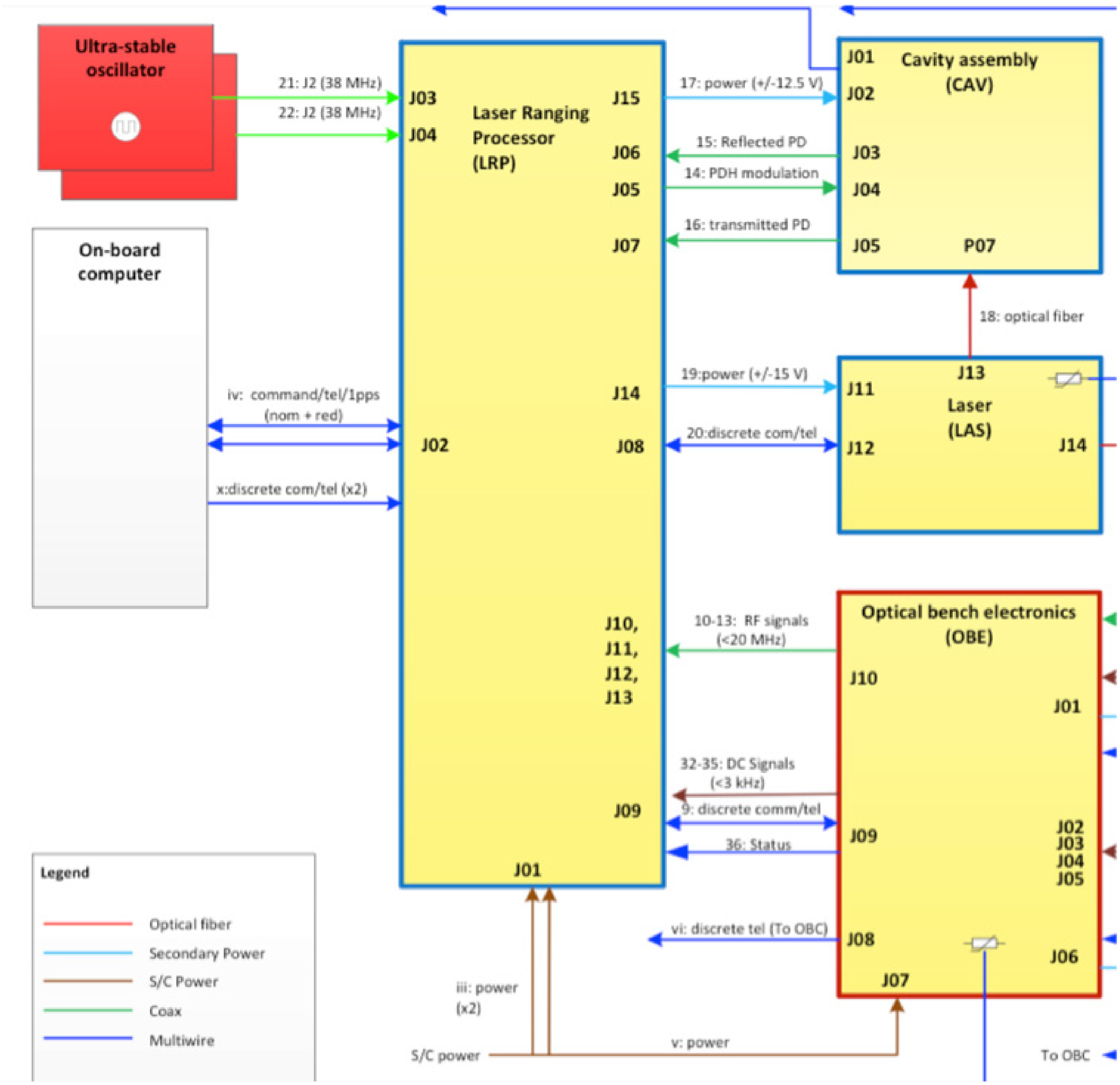

Figure 8 The L3 Phasemeter interfaces are expected to be the same as for the reduced version built for GRACE Follow-On except for the following: the 4 photoreceiver inputs from the Optical Bench Electronics will include 26 inputs on LISA (TBC, based on exact bench configuration); laser power will not be provided by the LRP; laser tuning characteristics could be identical if a Tesat laser is baselined as the master source in the Laser, otherwise it will change; the Cavity interfaces will be exactly the same if NASA provides the Phasemeter and Cavity; the power interfaces will be redundant on L3.

Current Status

NASA/JPL has two directly relevant phasemeter developments:

- A fully functional LISA Phasemeter has been developed to TRL4/5 including photoreceivers, analog signal chain, and digital signal processing core. This system demonstrated the LISA mission's measurement architecture, Time-Delay-Interferometry for the first time.

- A phasemeter has been developed to Flight maturity for GRACE-FO LRI. The LRI phasemeter represents relevant flight heritage for a L3 mission. While several phasemeter performance requirements on the LRI are relaxed compare to the LISA mission requirements, the LRI phasemeter is expected to meet the LISA requirement levels.

Proposed SAT activities advance the maturity of the LISA Phasemeter based on the recent experience developing a flight Phasemeter for the LRI. The three main objectives are to:

1. Incorporate the flight GRACE Follow-on LRI phasemeter developments into the TRL4 LISA design used extensively in the JPL LISA interferometer testbed.

2. Evaluate the LRI Phasemeter against LISA's more stringent requirements in order to identify required design changes.

3. Advance the design maturity of the LISA phasemeter through an architecture study to maintain the viability of the Phasemeter as a contribution to ESA's L3 gravitational wave mission.

This testing of the LRI phasemeter at the LISA requirements will be completed under proposed SAT funding, or can be accelerated with additional funding. The primary development is threefold: 1) Scaling the number of input channels from 4 to ~30, 2) scaling the number of tracked channels from 5 to 60, and 3) adding redundancy. Both variations are addressed in an earlier trade study but should be repeated in light of the flight developments for GRACE-FO.

Several performance metrics may be able to be improved over current performance with choice of difference samplers, for example, but existing performance can likely support a L3 mission.

Major Activities to Reach PDR

The Phasemeter would require "normal engineering" to scale up to the number of channels required, so there is a fair bit of engineering to do, ideally producing a prototype for PDR; this is not strictly required.

To participate in the PEM Phase we could either produce a prototype, or support the PEM with lower fidelity components implementing the same measurement readout.

Key Considerations

Strategic Links: The Phasemeter provides the science readout of the interferometer and also records states of the critical hardware elements. Having NASA provide the phasemeter enables insight into the science data, the performance of the constellation, and is a natural entrée to system engineering discussions about all aspects of the interferometer design.

The same connection led in the days of LISA in substantive inputs to the design requirements. Since 1996 this has provided requirement support for the laser and interferometer, plus the following:

- Time Delay Interferometry (1999)

- Post-processing interpolation TDI – TDI made practical on a spacecraft (2003)
- Development of Arm locking - Use LISA arms as frequency reference
- Velocity-correcting Time Delay Interferometry (2004)
- Demonstration of clock noise suppression
- First experimental demonstration of TDI (2008)
- Invention of picometer phasemeter (US 7,511,469)
- Optical ranging to absolute accuracy to 0.2m rms
- Optical Communications on the laser link (20 kbps)
- Track very low light power (<3pW)
- Design of the GRACE Follow-On LRI (2012)
- Differential Wavefront Sensing Demonstrated
- Interferometer system engineering (US Co-Chair of Interferometry ITAT)
- Design of LISA TDI experiment for GRACE Follow-On LRI
- Design of LISA Arm Locking experiment for GRACE Follow-On LRI
- Developed Flight Cavity
- LISA Phasemeter on LRI

Like virtually all the considered technologies the phasemeter is not primarily sensitive to design trades within the range of variations on L3 considered.

NASA's leadership in phasemeter development for LISA made possible the Laser Ranging Interferometer on GRACE-FO, an Earth Science geodesy and climate Mission. Developing that mission to flight has substantially enhanced NASA's investment and positions us to make a similar contribution to L3.

Partnership Description

The NASA Phasemeter team has been discussing partnering with our colleagues at the Albert Einstein Institute (Hannover, Germany), following the model of our successful collaboration on GRACE-FO. The GRACE-FO collaboration grew out of our relationship developed during the LISA formulation period. This preliminary discussion sees the following possibility:

Design details and requirements would be worked with a parallel US/German management structure, with hardware implementation by NASA. The NASA delivered hardware would be a contribution to Germany as the presumptive interferometer leads for the member state collaboration. Presumably NASA would both be involved in testing, with the flight hardware testing first within NASA and then in a more integrated sense in Germany.

The details of which hardware would be included are being discussed. There are several viable places to draw the interface. NASA could provide at a minimum the Phasemeter including the digital phasemeter core with appropriate analog interfaces. Additional opportunities for contributions would include additional elements of the former LIMAS and the optical cavity.

These negotiations with our partners should be based on available resources and interests. Note that on GRACE-FO our Partners built the photoreceivers and analog signal chain and we provided the Phasemeter; on LISA NASA built all of that, and we have viable designs quite similar to the flight hardware developed by our German colleagues.

Our European partners have expressed a desire to use the cavity from GRACE-FO since its interfaces and performance are available as build to print items.

Telescope System

Overview

The telescope is an afocal beam expander that functions to transport laser light from one spacecraft to another to make a displacement measurement between proof masses on widely separated spacecraft. The telescopes transmit and receive simultaneously, and there are two in series with the displacement measurement in each arm, for a total of 6 telescopes to make a complete 3 arm mission. The two most challenging requirements are optical pathlength stability and scattered light performance. The telescope must maintain optical pathlength stability at the ~ 1 pm/√Hz level to enable a ~ 10 pm/√Hz displacement noise budget for each link. An off-axis design might be needed to meet the scattered light requirement to keep the transmitter from disrupting the measurement at the receiver. Although the telescopes are not used to make images, they still require diffraction-limited performance for efficient delivery of light from one sciencecraft to another and to make sure that the transmitted phase fronts are smooth and free from major aberrations to minimize jitter-to-piston noise coupling. The baseline design includes a focus mechanism that moves the M3 and M4 optics as a pair and is intended to be used in a set-and-forget mode with occasional adjustments as required after commissioning. **Figure 9** shows the latest version of the prototype telescope under test. Requirements have been taken from the NGO yellow book.

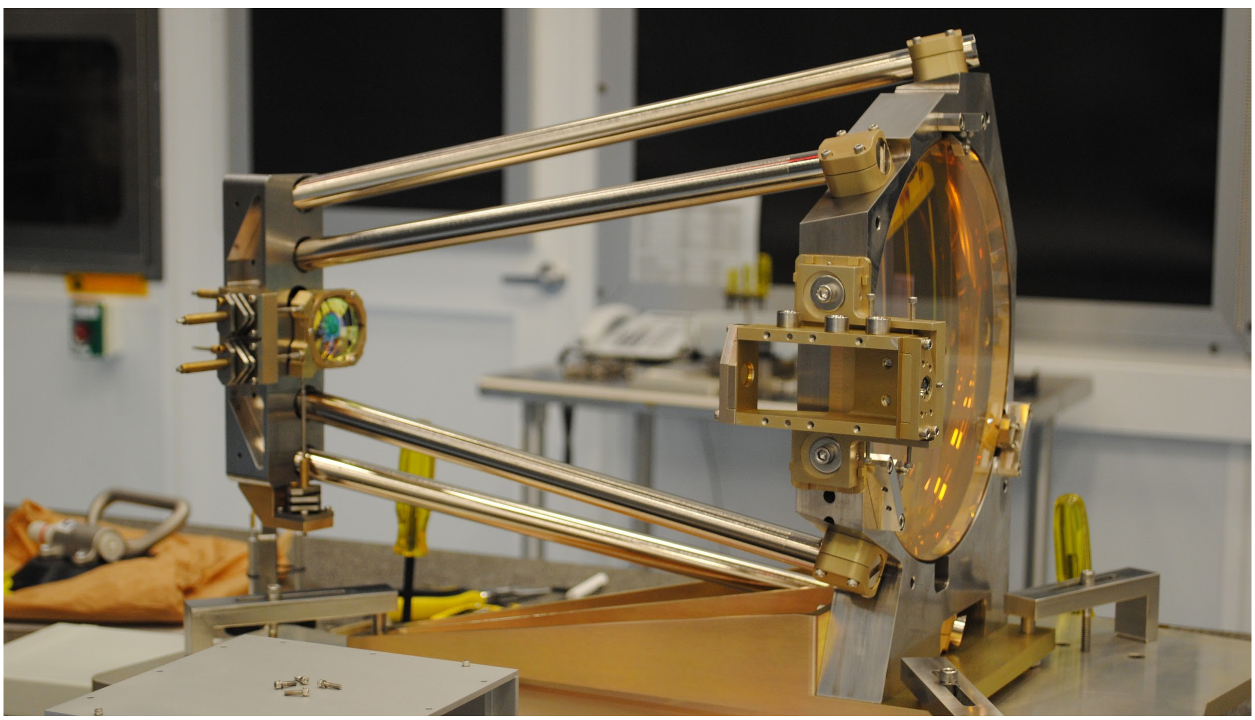

Figure 9: Telescope prototype undergoing testing at GSFC

Current Status

- Validating scattered light model
  The current prototype telescope is a 4-mirror off-axis design with a 20 cm primary and a 5 mm collimated output. The primary and secondary are an optimized Cassegrain design (parabolic primary and hyperbolic secondary), and the tertiary and quaternary mirrors

serve to collimate the beam and project the exit pupil backwards onto the optical bench. The telescope is made from conventional materials and has glass mirrors to keep costs under control. On-going testing is concentrated on validating a scattered light model and error budget at room temperature, with an emphasis on understanding how surface roughness and particulate contamination limit performance.

- Completed demonstration of dimensional stability with silicon carbide
  Earlier work in collaboration with the University of Florida demonstrated that the optical pathlength stability of an on-axis metering structure made from silicon carbide was limited by the thermal fluctuations in the test environment. The expected thermal fluctuations in the on-orbit environment are roughly two orders of magnitude smaller, leading to the conclusion that a silicon carbide structure could easily have the required pathlength stability.

- Developing a realistic design to demonstrate both pathlength stability and scattered light performance simultaneously
  The next prototype telescope design will incorporate the materials experience of silicon carbide with the scattered light lessons learned from the model validation to make a version of the telescope that we can test at the expected on-orbit soak temperature of -70 C (203 K) to demonstrate both the optical pathlength stability requirement and the scattered light requirement simultaneously. The design may incorporate silicon carbide mirrors and realistic mirror mounts.

Major Activities to Reach PDR

A reference mission design is required to set the requirements for PDR, but the chief sensitivity is through the arm length, which determines whether point ahead is required or not. The major technical milestones to get ready for PDR are:

- Develop an optical design that meets all requirements, including point ahead (if required), scattered light, and realistic interface requirements for the optical bench

- Investigate an in-field guiding solution if needed

- Develop a mechanical design including realistic mirror mounts, a focus mechanism (if required), and stray and scattered light apertures and baffling

- Develop a thermal model of the telescope integrated with the spacecraft

- Conduct a full-up STOP analysis of the design

- Develop strategies for local particulate contamination control (if needed) for meeting the scattered light requirement

- Full environmental testing of a qualification model

The main area for participation of the telescope in the PEM phase would be risk reduction work to specify, develop, and demonstrate the optical, mechanical and thermal interfaces with the optical bench.

Key Considerations

An important consideration is manufacturability. We will need a total of six flight telescopes, so the design must be robust enough to be manufacturable on a small scale, and have a careful interface definition so that the telescopes are functionally interchangeable enough to allow replacement of a broken or defective telescope during I&T without requiring complete realignment.

Two other important considerations are telescope articulation and point ahead/look behind. To a first approximation, telescope articulation is always required for any arm length, but point ahead may not be.

Telescope articulation is the variation in the line of sight of the telescope due to the orbital motion of the spacecraft. Typically this variation is large – on the order of +/- 0.75 degrees. The simplest solution is to mount the telescope to the optical bench and the GRS on the other side of the optical bench to form a complete optical assembly at the end of each arm. This assembly is then mounted so as to be able to move in the plane of the triangle formed by the three spacecraft. Previous work at GSFC has demonstrated an actuator with the required stability, control, and dynamic range. An alternative is in-field guiding. For this solution, one of the telescope mirrors is made to tilt (move in angle) without changing the path length through the telescope within the measurement bandwidth. It may be possible to do this without adding active metrology to measure the pathlength changes, but the other potential problem is that a realistic solution appears to require more back-end optics and may be difficult or impossible to implement without spoiling the scattered light performance.

Point ahead/look behind is the variation in angle needed to account for the finite light travel time between spacecraft. For a 5 million km armlength, the variation in the plane of the constellation is +/- 0.055 microradians, with a fixed offset of 3.3 microradians. Out of the plane, the variation is +/- 5.75 microradians with a fixed offset of 0.085 microradians. With a 40 cm diameter primary, a diffraction limited beam is 2.7 microrad, so it will be necessary to compensate for the variation out of the plane since that is 2 beamwidths. In the plane the field of view of the telescope should be enough to allow operation at a fixed offset, so only a single degree of freedom is required for the point ahead mechanism.

Telescope development in the US has concentrated on making an end-to-end design and addressing the key specifications of optical pathlength and scattered light performance. Funding has limited the ability to develop realistic telescope prototypes with flight-like materials and forced an approach that addresses the requirements one at a time. The effort in Europe, mainly at Astrium (now Airbus) has interpreted the pathlength stability requirement in terms of a zero-CTE design using composite materials. In our experience this materials choice suffers from dimensional instability due to moisture absorption, and we prefer to try a monolithic design based on a material such as silicon carbide. Further, the European off-axis optical design does not step the beam down from a 20 cm diameter input beam all the way to a 5 mm collimated beam interface with the optical bench, and therefore requires additional optics, which may cause difficulty in meeting the scattered light performance.

Partnership Description

The telescope has a key interface with the optical bench, and from the optical bench to the GRS, so if NASA were to supply the telescope we would need to work closely with the optical bench supplier. The optical bench for LISA Pathfinder has been developed at the University of Glasgow, and the same group has developed a preliminary design for a LISA-like mission. The GSFC group has collaborated with the Glasgow group to develop notional requirements for the placement of the exit pupil of the telescope and the detector, which has allowed the GSFC group to continue with its development of the telescope design.

A much more complete interface specification must be developed that includes stray and scattered light, optical pathlength stability, and the structure of the pupil interface beyond just the placement on the bench. In addition, the point ahead/look behind function is implemented on the optical bench. The telescope design must be compatible with these functions. This interface definition and testing activity could/should be part of the PEM phase, but we would want to refine the telescope design well before PDR. A careful (and perhaps reciprocal) requirements review would be a good place to start.

The telescope must also interface thermally and mechanically with the entire spacecraft to make sure that fluctuations in solar irradiance and fluctuations in the power dissipation of the avionics do not limit the optical pathlength stability. Preliminary modeling shows that there may be a mechanical stability and thermal gradient problem because the natural soak temperature of a telescope made with a material with high thermal conductivity such as silicon carbide is -70 C (203 K), and the optical bench needs to be maintained near 0 C (298 K) to take advantage of the low CTE of Zerodur. The thermal and mechanical interface argue for early involvement with the spacecraft designers.

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