

LISA Telescope Development Status and Flight Design

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ABSTRACT

The study of the universe through gravitational waves will yield a revolutionary new perspective on the universe, which has been intensely studied using electromagnetic waves in many wavelength bands. A space based gravitational wave observatory will enable access to a rich array of astrophysical sources in the measurement band from 0.1 mHz to 1 Hz. A space based mission complements ground based gravitational wave observatories, which typically search for signals at higher frequencies. LISA is a space based gravitational wave mission. Telescopes are one of the technology contributions from NASA to the European Space Agency (ESA) for the Laser Interferometer Space Antenna (LISA) Mission. ESA adopted the LISA mission in January of 2024. We will describe the key requirements for the flight telescopes and summarize the current status of the technology development effort.

Keywords: LISA, gravitational waves, optics, telescope

1. INTRODUCTION

The study of the universe through gravitational waves will yield a revolutionary new perspective on the universe, which has been intensely studied using electromagnetic waves in many wavelength bands. Gravitational waves were first detected on the ground by a LIGO¹ network from a pair of roughly 30 solar mass black holes merging nearly 100 years after Albert Einstein unveiled the General Theory of Relativity. The first nanohertz signal was detected in 2023². Gravitational waves are created during events such as supermassive black hole mergers, or collisions between two black holes that are billion times bigger than our Sun. These collisions are so powerful that they create distortions in spacetime, known as gravitational waves. Gravitational waves could also come from other distant systems including smaller stellar mass black holes orbiting supermassive black holes, known as Extreme Mass Ratio Inspirals (EMRIs). A space based gravitational wave observatory will enable access to a rich array of astrophysical sources in the measurement band from 0.1 mHz to 1 Hz and nicely complement observations from ground based detectors. First concepts for space based mission, Laser Interferometer Space Antenna (LISA) were developed in 1970s. Studies continued over the decades both in the US and Europe. ESA flew a technology demonstration mission called LISA Pathfinder³ in 2015. It demonstrated free falling test masses technology. LISA space mission was proposed by LISA consortium in 2017. ESA's Science Program Committee approved the LISA mission⁴ in January 2024 (Mission Adoption). It is an international collaboration between ESA, member states, and NASA. ESA leads the LISA mission and will provide the spacecraft, launch, mission operations and data handling. ESA member states and NASA will provide the key payload elements. LISA launch is planned for 2035. NASA will provide the ultra-stable lasers, telescopes and the UV light sources for test mass discharge. This paper discusses development of the telescopes for the LISA mission.

2. LISA MISSION OVERVIEW

There are many astrophysical phenomena that are either very dim or completely invisible in any form of light that astronomy has relied on for 400 years. Gravitational waves are a powerful new probe of the Universe that uses gravity instead of light to take measure of dynamical astrophysical phenomena. Studying gravitational waves gives enormous potential for discovering the parts of the universe that are invisible by other means, such as black holes, the Big Bang, and other, as yet unknown, objects. LISA will complement our knowledge about the beginning, evolution and structure of our universe.

The Gravitational Wave Spectrum

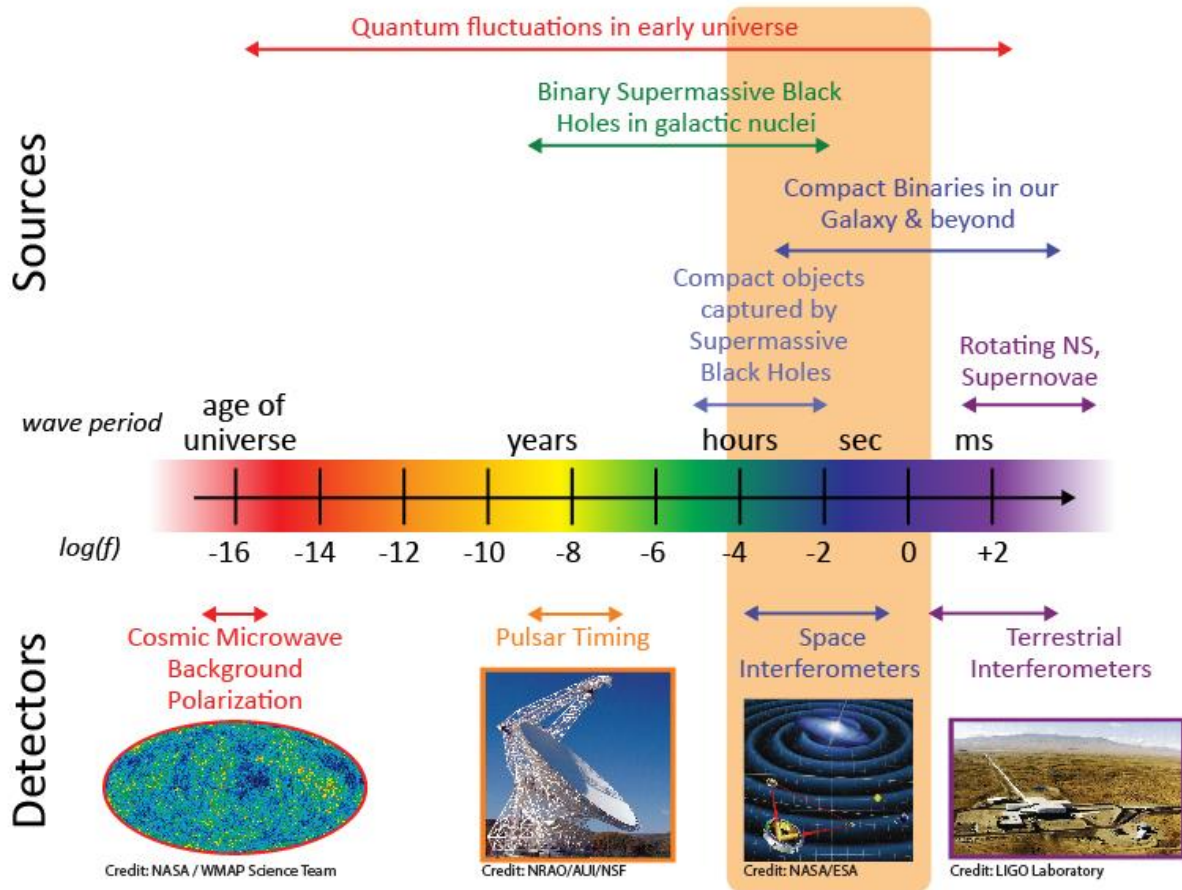


Figure 1. Gravitational wave spectrum.

The gravitational wave spectrum covers a broad span of frequencies as shown in Fig. 1. LISA operates in the low frequency range, between 0.1 mHz and 1 Hz (compared to LIGO's frequency of 10 Hz to 1000 Hz). The difference means that the gravitational waves LISA is looking for have a much longer wavelength, corresponding to objects in much wider orbits and potentially much heavier than those that LIGO is searching for, opening up the detection realm to a wider range of gravitational wave sources.

LISA consists of three spacecraft flying in an equilateral triangle formation separated by 2.5 million kilometers in an Earth-trailing, heliocentric orbit (Figure 2). These three spacecraft relay the 1064 nm coherent laser light back and forth between the different spacecraft and the signals are combined to search for gravitational wave signatures that come from distortions of spacetime. A bit like the objects moving on the surface of a pond produce ripples and waves, massive objects moving in space distort the fabric of spacetime and produce gravitational waves. Some of these gravitational wave events will cause the three LISA spacecraft to shift slightly with respect to each other, as they "ride the gravitational waves", to produce a characteristic pattern in the combined laser beam signal that depends on the location and physical properties of the source. These signals are extremely small and require a very sensitive instrument to detect. For example, LISA aims to measure relative shifts in position that are less than the diameter of a helium nucleus over a distance of 2.5 million kilometers, or in technical terms: a strain of 1 part in 10^{20} at frequencies of about a milli-hertz.

LISA measures gravitational radiation by precisely monitoring the tiny change in the proper distance between pairs of freely falling test masses. These masses are separated by 2.5 million kilometers and using a laser heterodyne interferometric technique, the change in their proper separation is detected to ~ 10 pm over timescales of 1000 seconds, a fractional precision of better than one part in 10^{20} . Freely-falling test mass technology was demonstrated by LISA Pathfinder³ flown in 2015. Distance measurement is done in three parts: spacecraft to test mass, spacecraft to spacecraft, spacecraft to test mass (Figure 4) and signals are combined to find the gravitational wave signature. Optical telescopes are essential for the implementation of this precision displacement measurement. LISA payload key subsystems are shown in Figure 3. Each spacecraft has two Movable Optical Subassemblies (MOSAs) that consists of a telescope, optical bench (OB) and gravitational reference sensor (GRS) that houses the test mass. LISA mission operational phase consists of 2 year cruise and commissioning phase followed by 4.5 years of science operations with +6 year potential extended mission.

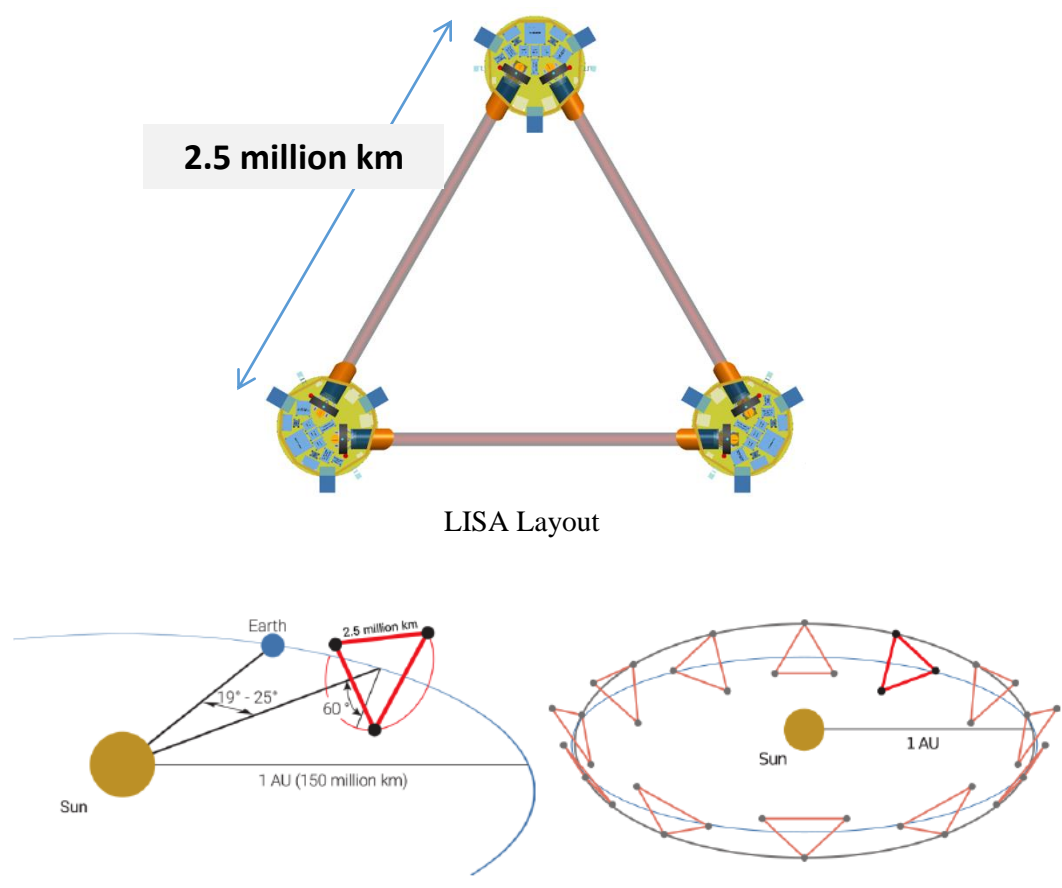
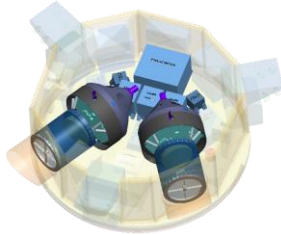


Figure 2. LISA mission summary. Three spacecraft separated by 2.5 million kilometers on a heliocentric orbit. Constellation Triangle rotates once per year as it orbits.

Moveable Optical Subassembly (MOSA) geometry



Two MOSA's per Spacecraft

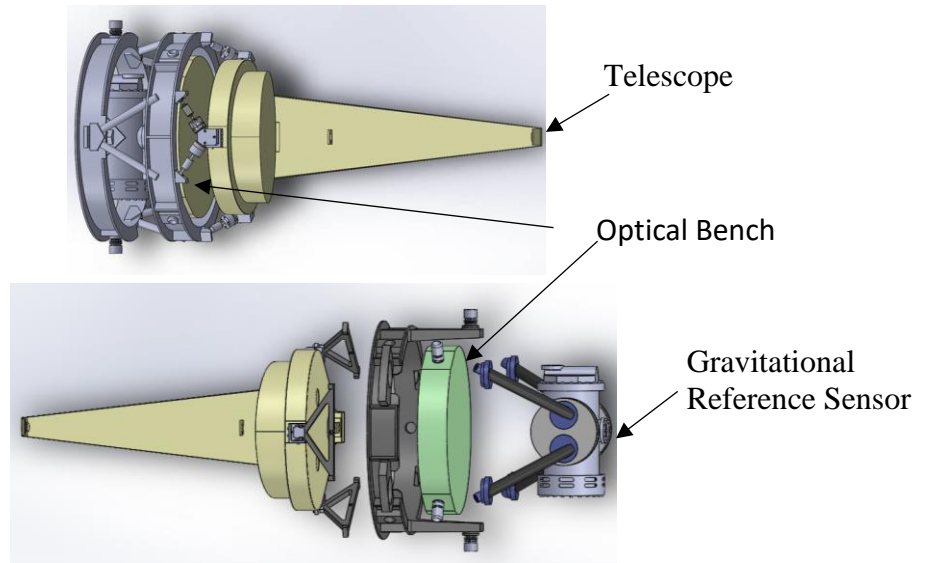


Figure 3. LISA payload key subsystems.

3. TELESCOPE DEVELOPMENT

One of NASA's contributions to the LISA partnership with ESA is to supply the precision telescopes to efficiently deliver power on-axis between spacecraft separated by 2.5 million km. The telescopes will simultaneously transmit and receive (TX/RX) 1064 nm coherent laser light (Figure 4). The transmit and receive transmissions are polarized either linearly or circularly allowing the telescope to transmit and receive simultaneously with the detection system in the other spacecraft. The detection system measures very small displacements on the level of a few picometers. Therefore, changes in the telescope metering or figure will have serious impacts on the sensitivity of the system and the ultimate success of the mission. The stability required for LISA is $1 \text{ pm}/\sqrt{\text{Hz}}$ at frequencies of 0.1 mHz to 1 Hz. The telescope dimensional stability is a key factor in the success of the LISA mission.

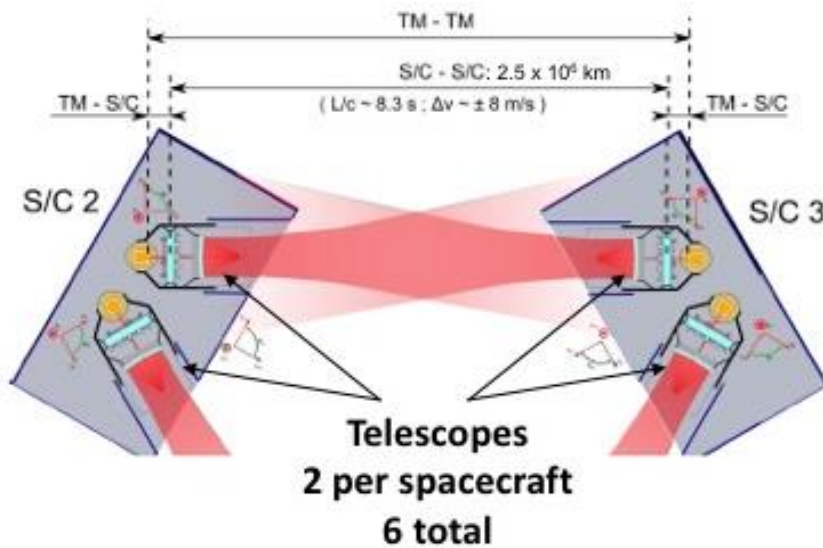


Figure 4. LISA optical metrology system.

Each spacecraft has two telescopes. They are afocal beam expanders with 302.5 mm diameter large beam. The beam diameter on the optical bench is 2.24 mm in diameter. The magnification is 135X. The primary mirror is oversized to allow for alignment adjustment with the beam alignment mechanism on the optical bench. The key telescope challenges and design drivers are the dimensional stability, low coherent backscatter and tilt-to-length coupling. Dimensional stability requires low coefficient of thermal expansion (CTE) material and thermal stability at $1 \times 10^{-5} \text{ K}/\sqrt{\text{Hz}}$ level. This can be achieved with thermal baffle(s) attached to the spacecraft. LISA Pathfinder⁵ demonstrated $1 \times 10^{-3} \text{ K}/\sqrt{\text{Hz}}$ level spacecraft stability. The low coherent backscatter can be achieved with unobstructed optical design and plan the design to accommodate contamination. The mirror coatings need to be low scatter and the telescope structure needs to be dimensionally stable so that the scattered light phase is stable. Additionally the spacing between the telescope and optical bench has to be stable. The optimum tilt-to-length coupling requires careful design to minimize pathlength differences with field angle (dOPL vs Field), careful alignment of measurement axes (optical bench to optical bench and optical bench to GRS) such that spacecraft jitter does not couple to the length measurement. Alignment mechanisms on the optical bench help optimize any residual coupling after integration. The wavefront errors projected into the far-field will also couple TX angular jitter into an apparent length signal. Therefore wavefront error needs to be low, WFE < 40 nm RMS or 1/30 at 1064 nm. The key telescope optical specifications are shown in Table 1. The telescope also supports the Constellation Acquisition Sensor (CAS), providing a larger field-of-view for the acquisition of the constellation than for the science optical chain.

Table 1. Key telescope optical specifications.

Specification	Value	Units	Comments
Wavelength	1064	nm	Nominal system operating wavelength
Conjugates	Afocal		Telescope is an afocal transceiver. Specifications generally assume "receive" mode, where the entrance pupil is the "large" pupil in inertial space
Field of view for Acquisition	+/- 225	μrad	Circular field of view
Field of view for Science	+/- 20	μrad	Circular field of view
Wavefront error	< 40	nm	Over the science FOV
Large Pupil diameter	302.5+/- 2.5	mm	Large pupil is associated with M1, inertial space
Small pupil diameter	2.24	mm	Small pupil is located at the system stop on the optical bench
Base ray deviation from optical axis (large pupil)	< 10	μrad	The "base ray" is the center-field center-pupil ray. Boresight error associated with the large pupil
Intrinsic Tilt-to-length (TTL)	< 0.6	pm/nrad	As-built over the science FOV

4. LISA ENGINEERING DEVELOPMENT UNIT (EDU) TELESCOPES

To demonstrate that telescopes meeting LISA requirements can be built we initiated a technology development program to verify that the selected structure, telescope design and material meet the LISA performance requirements. Our technology development partner is L3Harris Technologies in Rochester, NY. Three telescopes were built, Structural Thermal Model (STM), and two Engineering Development Units. They were built using a single low thermal expansion material, Zerodur®. The optical design is unobstructed to minimize backscatter. These telescopes have adhesive joints between structural elements as well as small optics and use bipod interfaces to the MOSA support structure (MSS). The

primary mirror is oversized for the 300 mm beam to allow for alignment adjustment optimization of alignment with the optical bench. The optical layout is shown in Figure 5 and telescope characteristics in Table 2.

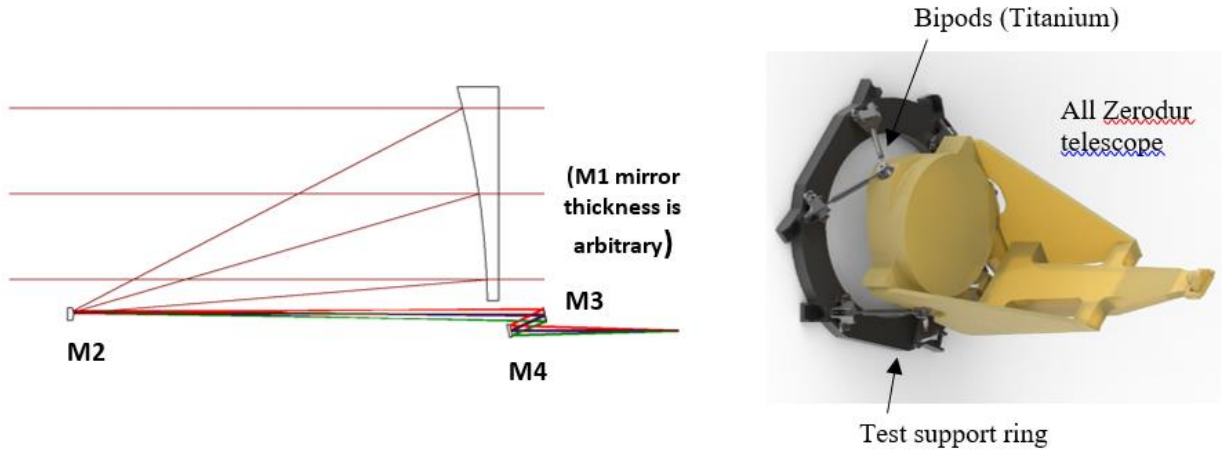


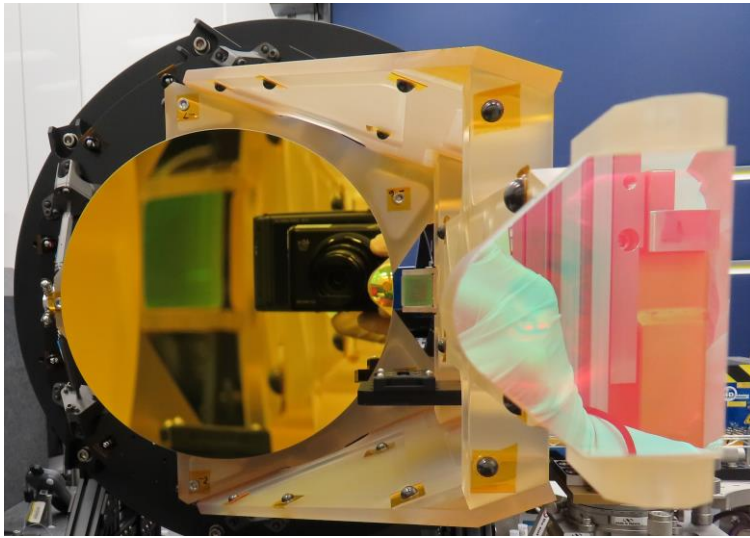
Figure 5. LISA Engineering Development Telescopes Layout

Table 2. EDU telescopes characteristics.

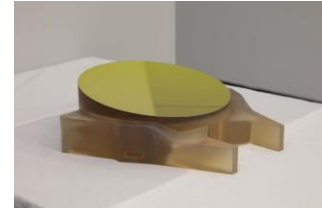
	Type	Conic	Radius (mm)	Clear (mm)	Aperture	Edge (mm)	Diameter
M1	Parabola	-1	-1475.246	345.3		365	
M2	Hyperbola	-1.0928	-25.813	6.4		25.4	
M3	XY Polynomial	0	Infinity	24.6		27.4	
M4	Flat	0	Infinity	21.0		27.4	

The Structural Thermal Model (STM) was successfully assembled. It demonstrated nearly flawless machining of complex Zerodur® parts. The optical components were not fully finished to optical quality. The STM successfully demonstrated telescope build process. Minimal-to-zero redesign or process changes were required. The STM experienced failure during environmental testing. Testing has been performed to inform root cause and corrective actions. The primary root cause is determined to be the CTE difference between the Zerodur® and titanium mount pads. STM was repaired and delivered to University of Florida for stability testing. Final data analysis is in progress.

The Engineering Development Unit 1 (EDU1) (Figure 6) optical components were fully finished and demonstrated nearly flawless finishing of optical components including coating of the M1 mirror with protected gold. M1 was successfully assembled to support structure and verified to have surface figure error of <7nm RMS. Next step was the integration of gussets to the tower and M1 assembly followed by integration and alignment of M2 and M3/M4 subassembly. Multiorientation fully assembled telescope optical testing demonstrated excellent wavefront error of <22nm RMS (Figure 7). Surface features in Figure 7 are well within LISA requirements and have no impact on LISA performance. Therefore they were not smoothen out. EDU1 telescope was delivered to Goddard Space Flight Center (GSFC) on May 1st 2024 (Figure 8).



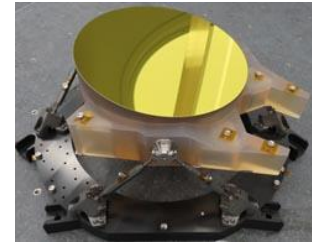
EDU1 after M2 integration



M1



M2



M1 assembly

Figure 6: Engineering Development Unit 1 (EDU1). Images Credit: L3Harris Technologies

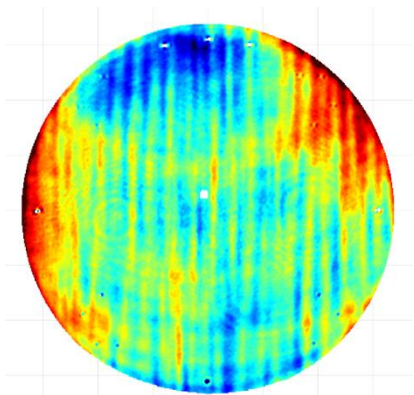


Figure 7: EDU1 Telescope Center Field WFE Plot. Average of Two Orientations. Image credit: L3Harris Technologies.

The Engineering Development Unit 2 (EDU2) assembly is partially completed. M1 mirror was finished to achieve surface error of <5 nm RMS surface figure error. Structural components including tower, gussets, and brackets were successfully completed as well as M2, M3 and M4 optics. The M1 mirror was assembled to support ring and gussets to tower and M1A were integrated. EDU2 was not fully finished due to LISA schedule constraints. To meet the LISA flight schedule the flight telescope procurement has to start as soon as possible.



Figure 8: EDU1 arrival at GSFC and incoming inspection. Images Credit NASA/Denny Henry.

Upon completion of incoming inspection of EDU1 testing at GSFC started. First step was the post shipment CMM measurements. They completed successfully. Optical testing is in progress. The test setup consists of a 600 mm auto collimating flat (ACF) with ~ 5 nm rms SFE over a 300 mm beam spot. The Optical Bench (OB) team has provided an aperture stop for our test program. The plan is to map the WFE (Wavefront Error) over many different pupil spots and field angles. The metrology equipment has been fully automated to avoid human disturbance and speed things up. Upon completion of these test activities optical path-length stability testing will be performed. A facility will be set up at GSFC to perform this test. Test facility planning is in progress.

5. PATH TO FLIGHT TELESCOPES

Next step in the LISA telescope program is the flight telescopes procurement. Working closely with ESA and the Optical Bench team manufacturing specifications for the flight telescopes have been finalized. Flight telescope program consists of at least six flight units and appropriate spare and test units. To mitigate schedule and cost risk the design goal is have a robust design for fabrication and alignment producing good yields. This can be accomplished with tolerances that are well within the state of the art and simplifying shapes that need to be machined. In addition testing of bonded joints to guide mechanical interface work on the flight units is in progress at GSFC. This includes materials for mount pads and adhesives as well as geometries. The flight vendor will still provide a design, and their processes will still need a qualification campaign.

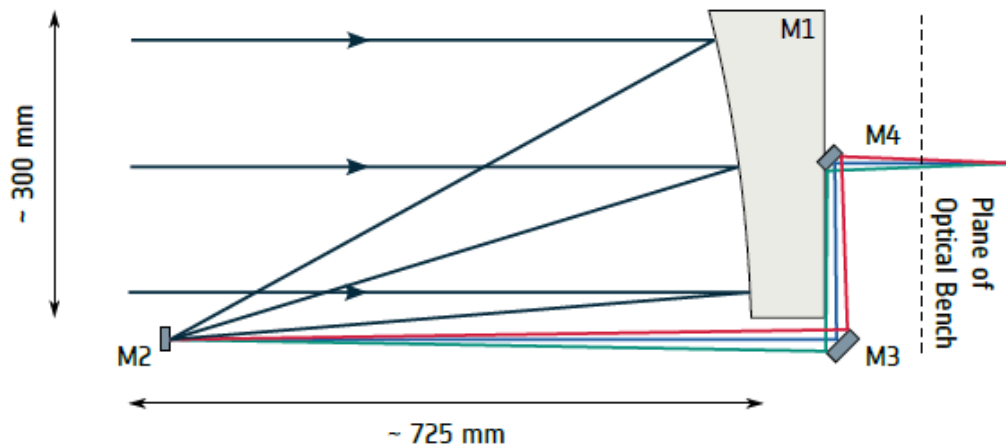


Figure 9: Reference flight design optical layout. The perimeter of the optical bench is only shown schematically, to indicate the location of its surfaces with respect to the beam's propagation path.

The optical layout for the flight telescopes will be updated in order to minimize the coupling of angular jitter at the telescope/optical bench interface into a pathlength signal (Figure 9). The light telescope design has 4 mirrors as in the EDU design and while it is still unobstructed and not on-axis in the usual sense. The beam is brought back to the center axis when it is exchanged with the optical bench. The magnification is 135x.

6. SUMMARY

LISA is the first mission to detect and study gravitational waves from space. It will perform time domain, all sky survey of millihertz band gravitational waves. One of the key NASA-provided hardware elements for the LISA mission are the telescopes. To demonstrate that the selected structure and telescope design and material meet the LISA performance requirements NASA initiated an Engineering Development Unit telescope program. The effort successfully met the goals of the program. LISA is ready to proceed with flight telescope development.

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