Research Article

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A telescope for LISA – the Laser Interferometer Space Antenna

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Abstract: Gravitational waves are a prediction of Einstein's general relativity theory. In autumn 2017, the Laser Interferometer Gravitational-Wave Observatory (LIGO; https://www.ligo.caltech.edu/) experiment reported the first detection of gravitational waves in addition to electromagnetic radiation from the collision of two neutron stars. This marks the first time that a cosmic event has been viewed in both gravitational waves and light and opens the door to a new type of astronomical observatory based on gravitational waves. The gravitational wave spectrum covers a broad span of frequencies and requires both space- and ground-based observatories to cover the full range. Space-based gravitational wave observatories, such as the proposed Laser Interferometer Space Antenna (LISA), operate at frequencies between 0.1 mHz and 1 Hz and complement the frequency range of 30–1000 Hz accessible by ground-based gravitational wave observatories, such as LIGO. A rich array of high-energy astrophysical sources is expected in the LISA measurement band. LISA was selected in 2017 as the third large mission of the Cosmic Vision program of the European Space Agency. The National Aeronautics and Space Administration will collaborate on both the scientific and technical aspects of this mission. This paper addresses the design of the optical telescope as an essential component of LISA's long-distance interferometric measurement system.

Keywords: gravitational waves; laser interferometry; space missions; telescope design.

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1 Introduction

The study of gravitational waves has enormous potential for discovering parts of the universe that are invisible by other means, such as black holes, the Big Bang, and other yet unknown objects. Laser Interferometer Space Antenna (LISA) will enhance our knowledge about the beginning, evolution, and structure of the universe. The frequency band accessible to LISA will make it possible to observe a wide range of gravitational wave sources that are of strong interest to the astrophysics of black hole and galaxy formation, to tests of general relativity, and to cosmology. This includes massive black hole mergers at all red shifts, extreme mass ratio inspirals, the inspiral of stellar-origin black hole binaries, known binary compact stars and stellar remnants, and potentially other sources such as relics of the extremely early universe and sources that are as yet unknown [1].

A gravitational wave observatory requires many technologies to enable measurements. One critical technology is to isolate test masses from all known forces so that they are freely falling in inertial space, with gravity being the dominant residual force. This is known as drag-free flight. The LISA Pathfinder mission launched in December 2015 demonstrated this technology in spectacular fashion, exceeding all expectations and demonstrating the performance required for the LISA observatory [2].

Another crucial technology is the ability to measure displacements on the order of 10 pm/√Hz over baselines of millions of kilometers. The measurement technique, heterodyne interferometry, requires dimensionally stable diffraction-limited optical telescopes. This paper describes the requirements and preliminary design options of a LISA telescope. To illustrate the flow down of requirements from the mission requirements, the measurement principle and mission architecture leading to the telescope requirements and design drivers are discussed in the following section. Section 3 elaborates on the required telescope functions and the key requirements followed by a description of design options (Section 4). Section 5 provides a summary of the further trade-offs considered for the telescope design and the path to arrive at a baseline design. A summary of this paper is provided in the last section.

2 Measurement principle and mission architecture

Gravitational waves are a propagating strain field in spacetime. The physical effect is to stretch spacetime in one direction and simultaneously shrink it in the orthogonal direction in a plane transverse to the direction of propagation. There are two distinct polarizations, called the ‘plus’ and the ‘cross’, and the changes to spacetime may be measured with a Michelson interferometer with arms at 90°. The characteristic size of the strain DDL/L is ~10^{-21} m/√Hz [1], corresponding to a displacement measurement of ~10×10^{-12} m/√Hz (10 pm/√Hz) over a baseline separation of 2.5×10^9 m or 2.5×10^6 km [3].

LISA consists of three interferometers, each at the vertex of a constellation of three identical spacecraft arranged in an equilateral triangle inclined at 60° to the plane of the ecliptic. Each arm of the triangle has a drag-free test mass at either end of the link, and the displacement between the test masses is measured through a pair of telescopes with a heterodyne laser interferometer. Displacement measurements are compared between adjacent arms to look for the coordinated stretching and shrinking signature expected from a gravitational wave. The triangular constellation allows the simultaneous measurement of both polarizations with three spacecraft.

Figure 1 shows the planned orbits for the LISA spacecraft. These orbits consist of three Earth-trailing heliocentric orbits, between 50×10^6 and 65×10^6 km from Earth. The orbital parameters will be optimized so that the mean distance between S/C is 2.5×10^6 km with an arm length change rate of less than 8 m/s over the extended mission duration (10 years). The average opening angle within the triangular constellation is 60° and is allowed to vary by not more than 1° with a maximum rate of 1.2×10^{-2} deg/day over the extended mission duration. The three spacecraft will be inserted with a single Ariane 6.4 directly into an escape trajectory.

Figure 2 shows the arrangement of the spacecraft. The end-to-end displacement changes between test masses are made in three parts. The distance from one test mass to the optical bench is made with a ‘short arm’ laser interferometer over a distance of ~1 m. The distance between optical benches on a widely separated spacecraft is measured with a ‘long arm’ interferometer through a pair of optical telescopes, and at the far spacecraft, there is another short

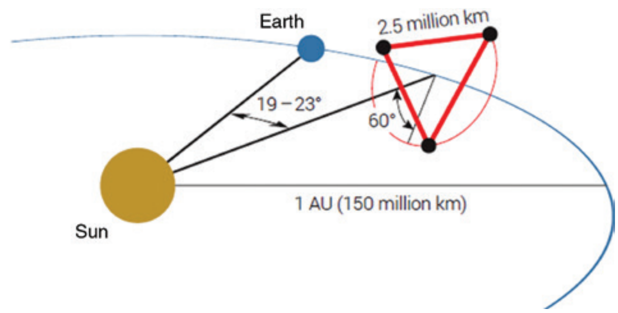

Figure 1: LISA orbit.

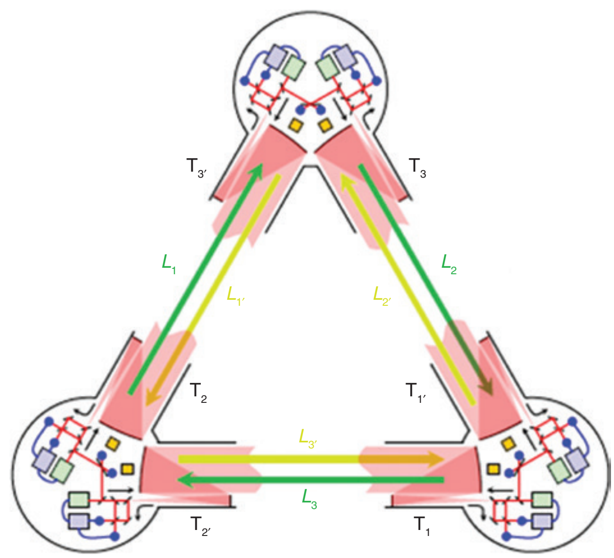

Figure 2: LISA measurement principle (three S/C depicting the long and local ‘arms’).

arm interferometer. The distance changes between the test masses caused by the gravitational waves to be detected are very small (10^{-12} m) and the laser signal attenuation over the long interferometer arms just due to diffraction is very high (from 2 W to 500 pW or about 10^{-10}) [1].

3 Requirements of the LISA telescope design

3.1 Functional description

As described in the previous section, the LISA instrument consists of three widely separated spacecraft arranged in an equilateral triangle, each containing two telescopes. The six LISA telescopes are part of the optical path of the interferometers and their function is twofold: on one hand, it has to transmit and receive a laser beam efficiently on axis to and from a distant spacecraft; on the other hand, it has to enable a precision displacement measurement between pairs of freely falling test masses in each spacecraft in the presence of external noise (such as jitter). Figure 3 shows the placement of the telescope in two of the three spacecraft. The instrument operates continuously, so the telescope must simultaneously transmit and receive light of the Nd:YAG frequency stabilized lasers at 1064 nm, which are used in the heterodyne interferometers for the optical path length measurements.

Optically, the telescope functions as an afocal beam expander, which converts a 2.24 mm diameter collimated beam (interface with the optical bench) into a 300 mm diameter collimated beam (size of the telescope primary mirror). Conjugate pupils are arranged to map the residual angular jitter of the spacecraft to angular motion about the center of gravity of the proof mass without lateral motion of the beam. The pupil is also relayed on the optical bench to the main science detector without lateral motion of the beam. This relay between the optical bench and free space is intended to minimize beam walk in all three spatial degrees of freedom. The lateral beam walk must be minimized to maintain the alignment of the interferometer optics on the bench and to ensure that the beam stays on the photoreceivers.

The telescope must be designed and mounted to minimize the conversion of the residual spacecraft angular jitter (on the order of 10 nrad/√Hz) into longitudinal optical path length noise. This conversion is referred to generically as tilt-to-length coupling, and if not minimized, it can exceed the interferometry displacement noise budget.

The conventional terminology of the entrance and exit pupil becomes confusing with the double use of the telescope receiving and sending light. The terms ‘external

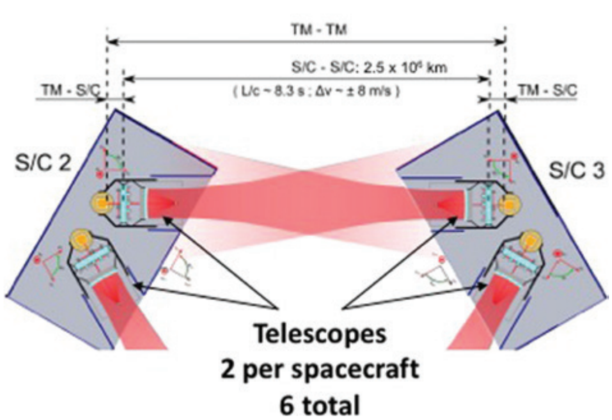

Figure 3: Telescope functional description.

and internal’ pupils are used instead. The placement of these pupils is at the test mass (external) and at a location inside the optical bench (internal). The test mass is some 500 mm behind the primary mirror. The 2.24 mm diameter internal pupil is located inside the optical bench, with a clearance from the last telescope mirror of more than 100 mm. The internal pupil on the optical bench is in fact the aperture stop of the system.

One additional requirement on the telescope design not often emphasized as a driving requirement is that the design must be robust enough for small-scale manufacturing and, to the extent possible, interchangeable and modular. It will be necessary to build 6 flight units plus one or two spares and one or two units for ground support testing, so a total of ~10 units will be required. A design that lends itself to simple alignment and construction techniques and generous tolerances will be an advantage in controlling cost and schedule risks.

3.2 Key requirements

The design of the LISA telescopes is driven by two critical requirements: the requirement for an extremely stable optical path length and the very low levels of coherent backscattered light that can be tolerated. Optical path length stability is required because the application of the telescope is precision length measurement. The light paths through the telescopes at both ends of the measurement link are in series with the total displacement measurement, so any change in the telescope’s path length enters into the science measurement of the LISA instrument directly. It is necessary to keep the optical path length of the laser light traveling through the telescope stable to 1 pm/√Hz, which requires a dimensionally stable telescope, and minimizing any tilt-to-length coupling. The requirement of very low coherent backscattered light is linked to the double function of the telescope sending a powerful laser beam and receiving a faint beam (2 W compared to ~500 pW). The precision displacement measurement is made with heterodyne interferometers that receive through the telescope, and the measurement equipment is extremely sensitive; hence, there is a need for a telescope designed to minimize coherent backscattered light.

The required optical quality of the telescope is not uniform over the full field of view as explained in this paragraph. During science operations, the spacecraft maintain the telescope line of sight pointing between the spacecraft with differential wavefront sensing using the main science detectors, which are four-segment quadrant diodes to control the attitude of the spacecraft. The instantaneous field of view must accommodate the point-ahead angle, a slight difference between the incoming wavefront from the far spacecraft and the angle at which the transmit beam must be pointed to find the far spacecraft after the light travel time between spacecraft, which is 8.3 s one-way. Over this field of view of 50 μrad, there are tight requirements on the wavefront error induced by the telescope (root mean square smaller than 30 nm, with special restrictions on some of the aberrations associated to low-order Zernikes) and the change of the optical path length as a function of field angle (<30 μm/rad at the interface with the optical bench). However, to get the telescopes properly pointed at each other during the set-up and commissioning phase of the instrument, the telescopes are scanned [4] over an uncertainty region with a CCD array, the constellation acquisition sensor, which looks through the telescope over a ±225 μrad field of regard. It is not necessary to maintain the full performance of the telescope over this field of regard, but the telescope must collect the light efficiently.

4 Telescope design options

This section describes some of the options for the telescope optical design to meet and fulfill the functional and performance requirements described above.

4.1 Materials choice

The optical path length stability through the telescope (1 pm/√Hz level) depends mainly on the telescope concept and the materials used.

The telescope is designed using all reflecting surfaces to avoid the possible optical path length changes that can occur due to the temperature dependence of the index of refraction of glass. For the selection of the materials, it is important to consider the two main environmental disturbances (both thermal) that change the optical path length in the LISA measurement band. These are the variations in the output power of the Sun and the power dissipation variations in the on-board avionics. These disturbances are managed using passive thermal shielding to get the local temperature fluctuations down to the 10 μK/√Hz level or below at frequencies near 0.1 mHz [5] and then using a very low coefficient of thermal expansion (CTE) material such as Zerodur, ULE, or Clearceram to minimize dimensional changes. Previous works [6, 7] have demonstrated that a metering structure made with a material such as silicon carbide, with a CTE of $\sim 4\times10^{-6}$, can meet the required optical path length stability with the expected on-orbit temperature fluctuations. Other materials have been studied as well [8]. The current option is Zerodur for both the structural and optical parts of the telescope because it allows a considerable relaxation of the thermal stability requirements, although it also requires operation near room temperature (~300 K).

4.2 On-axis versus off-axis

The requirement for very low coherent backscatter from the transmitter into the receiver is actually a twofold requirement. The basic displacement measurement is made with heterodyne interferometry. Any light from the transmitter that makes it to the detector is phase coherent and contributes parasitic interference fringes proportional to the electric field strength, which is proportional to the square root of the scattered optical power. This puts a premium on reducing the power, as even a part-per-million scattered light contributes a part-per-thousand electric field. If the phase of the scattered light is stable, then the scattered light fringes are stationary with respect to the main fringes. If the phase is modulated because the scattering surfaces are in motion, then it can create broadband noise in the measurement band. This means that the telescope and the optical system must be designed not only to minimize scattered light but also to keep the phase of light scattered into the receiver stable. Scattered light modeling of the telescope itself shows that most of the light is scattered from the mirror surfaces rather than the telescope structure, so a dimensionally stable telescope (stable optical path length) will help. The optical path length is already required to be at the 1 pm/√Hz level to support the interferometry [1], but the path length stability to the detectors located on the optical bench must also be kept stable. The current requirement for the mounting stability to the optical bench is set at the 100 pm/√Hz level to allow for a relatively high level of scattered light as might be expected from optics contaminated with particulates toward the end of an extended mission. In addition, the requirement for low coherent backscattered light drives the adoption of an off-axis telescope design [9]. In an on-axis design, the center of the secondary mirror always has a small spot that appears differentially flat and scatters directly back into the receiver. Sometimes called a ‘narcissus’ reflection, it is not yet been demonstrated that it is possible to suppress the reflection from the secondary enough to meet coherent backscattered light requirements with an on-axis design.

4.3 Optical concept

Although, in principle, there are a large variety of possible telescope design forms that could comply with the requirements described above, only the two concepts that have been analyzed in more detail by the project team so far are presented here.

The first option is an optimized combination of four mirrors in an off-axis configuration that consists of a Cassegrain and a back-to-front Schwarzschild concept. Figure 4 shows the basic design, with a parabolic primary, a hyperbolic secondary, and then a pair of mirrors to collimate the beam. The diagram shows the placement of the optical bench behind the primary. In operation, a 45° fold prism would bend the small aperture pupil parallel to the surface of the optical bench. The conjugate external pupil is virtual and located at the center of mass of the test mass to minimize the tilt-to-length coupling as described in the previous sections. The design has been optimized by increasing the primary-secondary mirror spacing so that the primary mirror is operated at F/1 and to keep the manufacturing tolerances within reach of common mechanical tolerancing and modern optical shop practices.

The second option is a hybrid of Paul and Korsch systems with a total of six mirrors. The first two mirrors act as the afocal system of the Paul concept and the third mirror of this concept is replaced by a three-mirror afocal Korsch. Thus, the system has five powered mirrors. One additional flat folding mirror is included to facilitate the accommodation of the telescope with respect to the optical bench. In addition, it yields extra degrees of freedom, which make it easier to control the exit pupil clearance; the penalty of increasing the number of mirrors is that they add complexity to the dimensional stability. This concept is shown in Figure 5 in which one possible configuration is shown, although the presence of a flat mirror opens other folding possibilities without introducing changes in the optical design.

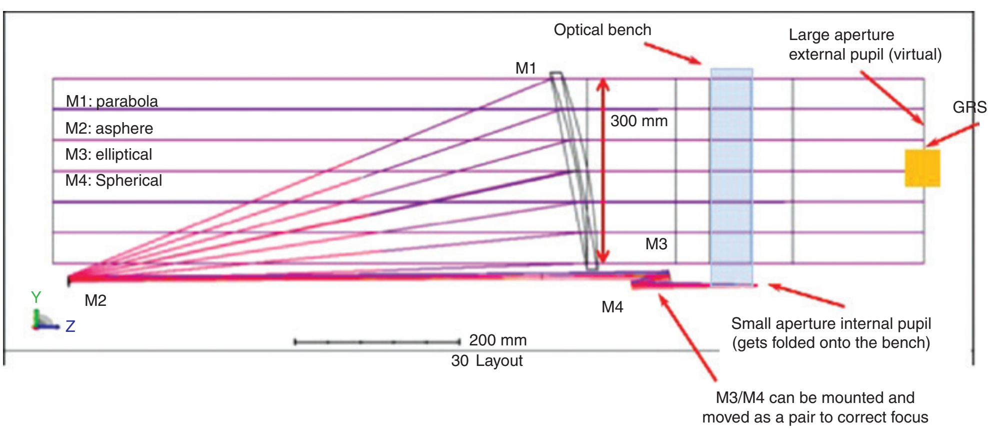

Figure 4: Cassegrain design form.

- Entrance/exit pupils: 300/2.24 mm
- Six mirrors: 2 parabolas 1 flat (folding) 1 ellipses 2 hyperbolas
- Exit pupil clearance: ~ 113 mm
- Distance M1-optical bench: ~110 mm, can be changed easily without a major impact on pupil clearance: folding flexibility.

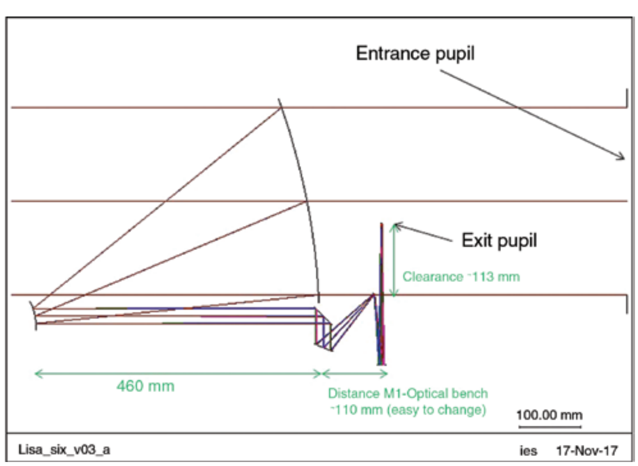

Figure 5: Korsch design form.

5 Further trade-off considerations and path to a baseline

The main top-level architecture trade for the LISA instrument is related to the three spacecraft constellation breathing angle compensation. Over the course of a year, celestial mechanics imposes a fluctuation in the vertex angle between arms of ±1°. For the compensation of the breathing angle of the constellation arms, there are two possible schemes currently considered: in-field pointing (IFP) and telescope pointing (TP). The trade-off between these two solutions involves different subsystems in the spacecraft and payload whose description is outside the scope of this paper. The key technologies that define this trade-off (namely the feasibility of the back link and issues related to wide-field telescopes) are the subject of ongoing development activities that will conclude within the timeframe of the phase A study, allowing a firm confirmation of the current baseline architecture (TP) to be made. No concept for the IFP telescope has been presented in this paper, but it should be noticed that IFP requires a wide-field telescope and wide-range beam steering mechanism stable within a few picometers in the science frequency band and involves scanning the beam over the telescope mirror surfaces by large amounts.

The telescope has, within the LISA instrument, interfaces to the adjacent optical bench and the gravitational reference sensor containing the free-falling test masses. Further trade-offs will have to take these subsystems into account, calling for careful interface management as to critically review the performance budget of the whole system. The assembly, alignment, and testing of the telescope also require careful assessment.

It is therefore envisaged to design and build an engineering model for the telescope assembly early in the LISA program to assess and confirm not only the manufacturing requirements but also the stringent requirements on the alignment verification and testing for the flight model. This includes not only the telescope itself but also the structure interfacing with the optical bench and the spacecraft.

With a projected launch date for LISA in 2034 or earlier, such an engineering model needs to developed, tested, and verified at least 10 years in advance, as it has implications for the design of the optical bench and the spacecraft. A confirmed telescope baseline must therefore be in place by mid-2019 to achieve this baseline. This would ensure that a Technology Readiness level 6 – meaning that the subsystem is verified in the relevant (space) environment – is reached before adoption.

6 Summary

This paper presents the key requirements for a telescope design optimized for the LISA mission. The design includes both the requirements and the trade-offs appropriate for a classical astronomical image-forming telescope as well as the requirements for a precision laser ranging measurement. Each telescope acts simultaneously as a transmitter as well as a receiver, with power level differences of ~10 orders of magnitude between transmit and receive. In addition, the telescope design has to be optimized to minimize noise for the overall performance of the three-satellite constellation that forms the complete observatory.

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