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LISA technology—concept, status, prospects

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Abstract
The existence of gravitational waves is the most prominent of Einstein's predictions that has not yet been directly verified. The space project LISA shares its goal and principle of operation with the ground-based interferometers currently under construction: the detection and measurement of gravitational waves by laser interferometry. Only in space, detection of signals below, say, 1 Hz is possible. LISA, a joint project of ESA and NASA, is a mission that will measure these low-frequency waves. LISA consists of three spacecraft in heliocentric orbits, forming a triangle with 5 million km sides. Launch for LISA is scheduled for 2011, following a technology demonstrator LTP in 2006.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The detection and measurement of gravitational waves is one of the great challenges for modern physics. Although predicted by Einstein in 1916, a direct observation of these waves has yet to be accomplished. Their detection would open a new window to the universe [1] and a new branch of astronomy.

Great hopes of such detection lie in the ground-based laser-interferometric detectors currently nearing completion. These ground-based detectors are sensitive in the 'audio' frequencies of a few Hz up to a few kHz. However, for all ground-based measurements, there is a natural, insurmountable boundary towards lower frequencies; namely the unshieldable effects due to varying gravity gradients of terrestrial origin: moving objects, meteorological phenomena, as well as motions inside the Earth.

To overcome this restriction, the only choice is to go far enough out into interplanetary space, preferably into an earth-like orbit. The space environment offers significant benefits: it eliminates terrestrial seismic and gravity gradient noise, provides an excellent vacuum along the arms, and enables the arm length to be chosen large enough to match the frequency of the

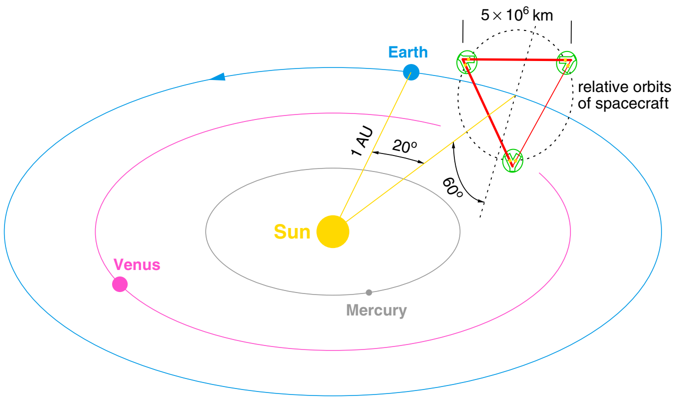

Figure 1. Orbits of the three spacecraft of LISA, trailing the Earth by 20°. The triangle arms are scaled by a factor of 10 in this illustration.

astrophysical sources we want to observe. This is the aim of the space project LISA (Laser Interferometer Space Antenna), which will cover the frequency range from about 10^{-4} Hz to 1 Hz.

2. The LISA concept

Since the late 1970s, ideas for gravitational wave detectors in space were proposed and various configurations have been studied in detail (for a brief historical review see the LISA publications [2–4]). This paper will give an overview of the current concept and technology of LISA, often referring to further contributions in this volume [5].

The LISA configuration. The project LISA, as laid down in the *Pre-Phase A Report* [2] of 1998 and then in the *System and Technology Study Report* [3] of 2000, consists of three identical spacecraft, placed at the corners of an equilateral triangle (figure 1). The sides are 5 million km long (5×10^9 m). This triangular constellation revolves around the Sun in an Earth-like orbit, about 20° (i.e. roughly 50 million km) behind the Earth. The plane of this equilateral triangle needs to have an inclination of 60° with respect to the ecliptic to provide the most uniform rotation of the triangle. The small orbit-correction manoeuvres required can be made with field-effect ion thrusters. The three spacecraft form a total of three (but not independent) Michelson-type interferometers, with 60° between the arms.

The LISA spacecraft. The spacecraft at each corner will have two optical assemblies subtending an angle of 60°, which are pointed towards the other two spacecraft (indicated in figure 2, with the Y-shaped thermal shields shown semi-transparent). An optical bench, with the test-mass cage at its centre, can be seen in the middle of each of the two arms, and a telescope of 30 cm diameter at the outer ends. Each of the spacecraft has two separate lasers that can be phase-locked so as to behave like the ‘beam-splitter’ of a Michelson interferometer.

The annual orbit of LISA. During its yearly motion around the sun, the three spacecraft of LISA will ‘roll’ on a cone of half-angle 60°, each spacecraft moving on a slightly elliptic and slightly inclined individual orbit around the sun.

This configuration has a number of advantages that make several of the design requirements less stringent. (1) The spacecraft face the sun at a constant angle of incidence

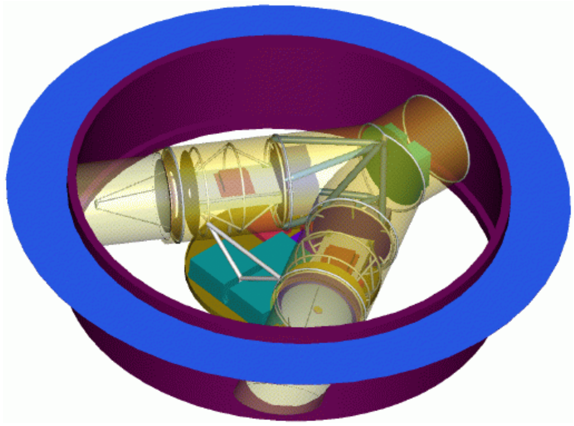

Figure 2. View of one LISA spacecraft, housing two optical assemblies (thermal shield shown as semi-transparent).

of 30°, which provides a stable thermal environment for the sensitive parts (optical assembly, the sensors) of the spacecraft. (2) The essentially unperturbed orbits of the three spacecraft provide a stable configuration, close to an equilateral triangle. Thus it is relatively easy to devise articulation schemes for the two ‘telescopes’ in each spacecraft to follow these small-angle deviations. (3) The centre of the LISA triangle trails the Earth in its orbit by 20°, or about 50 million km. This makes the distance to Earth (for radio communication) also quite stable, thereby reducing the problems in radio antenna design and radio transmission power.

3. The drag-free operation

The distances between the different spacecraft are measured from test masses ‘freely floating’ within these three spacecraft. Each spacecraft contains two test masses, one for each arm that forms the link to another LISA spacecraft. The test masses, 4 cm cubes made of an Au/Pt alloy of low magnetic susceptibility, reflect the light coming from the YAG laser and define the reference mirror of the interferometer arm.

The technique of ‘drag-free’ control is used to make sure that the spacecraft remain ‘centred’ on the masses without touching them, thereby shielding the masses from external disturbances, allowing them to be ‘freely floating’ as much as practically possible.

Gravitational sensor. So, as well as for defining the reference mirrors, the test masses are utilized as inertial sensors for the drag-free control of the spacecraft. Development of these sensors is being carried out at various institutions [6, 7]. These sensors feature a three-axis electrostatic suspension of the test mass with capacitive position and attitude sensing. A resolution of 10^{-9} m $\mathrm{Hz}^{-\frac{1}{2}}$ is required to limit the disturbances induced by relative motions of the spacecraft with respect to the test mass: for example, the disturbances due to the spacecraft self-gravity or to the test-mass charge.

FEEP thrusters. The very weak thrust ($<100\,\mu$N) required to maintain drag-free operation will be supplied by field-effect electrical propulsion (FEEP) devices: a strong electrical field forms the surface of liquid metal (Cs or In) into a cusp from which ions are accelerated to propagate into space with a velocity (of the order of 60 km s^{-1}) depending on the applied voltage. Such FEEP thrusters have been developed at two European institutions, namely

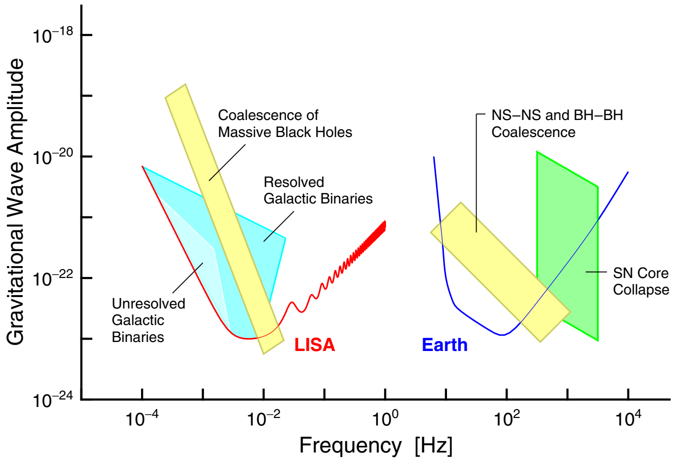

Figure 3. Typical sensitivities of GW detectors on Earth and in Space, and some sources that could be detected by them. For the LISA curve, a signal-to-noise ratio of 5, and averaging over one year and all possible directions and polarization angles is assumed.

Centrospazio, Italy [8] and Seibersdorf, Austria [9]; their characteristics will be studied in a technology demonstration mission (section 6).

4. Noise and sensitivity

This section will cover some of the most important noise sources in the LISA project, which then will be relevant also for other configurations, such as for LISA follow-on missions, the LISA technology demonstrator and for the Chinese project ASTROD [10].

Figure 3 shows sensitivity curves for the ground-based interferometers (Earth), as well as for LISA. In both cases the shape is that of a trough, with a steeper slope at the left than on the right. The regimes of best sensitivity hardly overlap.

The curve for LISA is again shown in figure 4, enlarged and in greater detail. This LISA sensitivity curve consists of three main parts, as indicated by the three differently shaded frequency regions, in which different noise mechanisms take hold.

Shot noise. With the 30 cm optics planned, from 1 W of infrared laser power transmitted only some 10^{-10} W will be received after 5 million km and it would be hopeless to have that light reflected back to the central spacecraft. Instead, the distant spacecraft are equipped with lasers of their own, frequency-locked to the incoming laser beam.

Due to the low level of light power received, shot noise plays a major role in the total noise budget of spurious displacements, defining the flat middle part of the sensitivity curve, the bottom of the trough.

The effect of shot noise is a spurious 'path difference' $\widetilde{\delta L}$ inversely proportional to the square root of the received power P. With an armlength increased by, say, a factor of κ, the power would decrease by a factor of κ^{-2}, and both the apparent spurious path differences $\widetilde{\delta L}$ and the optical path L would thus increase by an identical factor of κ. This means that the sensitivity of a space probe, other characteristics remaining the same, would have a shot noise limit for the strain $h \sim \delta L/L$ that is independent of the armlength, $L/2$. This is of importance when estimating the sensitivity of LISA follow-on missions with different armlengths.

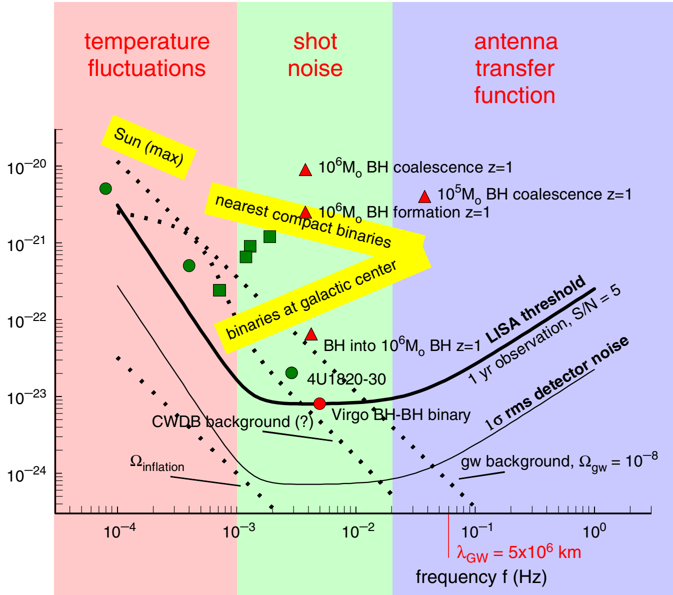

Figure 4. Sensitivity of LISA at enlarged frequency scale; the heavy curve 'LISA threshold' again represents the signal strength that would provide a signal-to-noise ratio of 5, averaged over one year. The frequency ranges of the major noise contributions are indicated by different shading.

Antenna transfer function. At higher frequencies, we have to take into account the antenna response that rolls off as $1/f\tau$ at frequencies f above the inverse of the round-trip time τ. Thus at these frequencies the shot noise leads to the frequency-proportional rise at the right-hand side of the sensitivity curve shown in figure 3 and, in more detail, in figure 4. For a more detailed discussion of the sources see, e.g., [1].

Acceleration noise. At frequencies below 1 mHz, the noise is mainly due to accelerations of the test mass that cannot be shielded even by the drag-free scheme: forces due to gravitating masses on the spacecraft when temperature changes their distances, charging of the test masses due to cosmic radiation, residual gas in the test mass housing. Except for the cosmic ray charging, the acceleration noise contributions are dependent on temperature variations, and this is why in figure 4 they come under the heading 'temperature fluctuations'. These accelerations have a rather 'white' spectral distribution, which thus results in position errors rolling off roughly as $1/f^2$.

Gravity gradient noise. The test mass, housed in the LISA spacecraft, is subject to the gravity field of the other masses that form part of the spacecraft. These masses, though 'rigidly' connected to each other, will undergo small changes in their positions, due, e.g., to changes in the temperature distribution.

This thermal distortion of the spacecraft is actually one of the most prominent sources of 'acceleration noise'. Elaborate calculations on the temperature fluctuations to be expected (e.g. from variations in the solar radiation) and on the thermal behaviour of the spacecraft's masses have resulted in a set of requirements for the LISA design [3].

Noise due to charging of the test mass. Cosmic radiation will cause the test mass to acquire an electrical charge, which will result in a number of noise effects. A broad discussion is given in the *LISA Pre-Phase A Study* (PPA2) [2].

These charges will give rise to electrostatic forces of attraction to the cage walls. Also, if not perfectly shielded by the cage and the spacecraft shields, the charges will be subject to Lorentz forces due to LISA's motion in the interplanetary magnetic field. Similarly, any changes in that magnetic field will also produce forces on the test mass.

Passive shielding is not sufficient to protect the test masses from the effects of charging. The charge accumulating on the test mass must be monitored, and continually discharged by shining ultraviolet light on the test mass [2, 11].

Noise due to residual gas. Many acceleration noise contributions are due to the residual gas inside the sensor. Although the test mass in its housing is provided with an extra vacuum of high quality, 10^{-8} mbar $= 10^{-6}$ Pa, the test mass will be subject to several non-negligible accelerations.

Foremost among these is the stochastic noise due to the buffeting by the impinging residual gas molecules. This statistical noise is proportional to the square root of the residual gas pressure, p. If the casing of the sensor has a temperature gradient, due, e.g., to changes in solar radiation or in the power dissipation in the spacecraft electronics, differences in gas pressure inside the sensor will build up. Here we must mention the so-called radiometer effect, and the effect of temperature-dependent outgassing of the cage walls.

Noise total. With a myriad of other, smaller, noise contributions the total apparent path noise amounts to something like $\widetilde{\delta L} \approx 40 \times 10^{-12}\,\mathrm{m\,Hz}^{-\frac{1}{2}}$ at the lowest part, the bottom of the trough. For signals monitored over a considerable fraction of a year, the best sensitivity is about $h \approx 3 \times 10^{-24}$, indicated in figure 3 by the curve marked 'LISA', and in more detail in figure 4. Some of the gravitational wave signals of sources indicated in figure 4 are guaranteed to be much larger, and so LISA stands an excellent chance of observing and measuring them [1].

5. Status of LISA

LISA is approved by ESA as a cornerstone mission under Horizons 2000. A *System and Technology Study* [3] has substantiated that improved technology, lightweighting and collaboration with NASA will lead to a considerable reduction of cost. Thus, a new approach is being pursued jointly by ESA and NASA, under the auspices of the LISA International Science Team, LIST. Launch is foreseen for 2011, not very long after first operation of the next-generation ground-based detectors. LISA has a nominal lifetime of two years, but the equipment and thruster supply are chosen to allow even ten years of operation. This volume [5], the proceedings of the *Fourth International LISA Symposium, Pennsylvania, 2002*, comprises a wealth of contributions on various aspects of LISA. These contributions all contain references to further literature.

LISA follow-on. Even as early as now concepts are being discussed for a successor to LISA, with possible enhancements in sensitivity and/or frequency band. One scheme would try to bridge the frequency gap between ground and space detectors, by reducing the armlengths, leaving the general configuration unchanged.

Another concept is to have a square constellation instead of the triangle, providing pairs of independent interferometers. These can be used to detect and measure a stochastic background of gravitational waves, reaching much further back than the 3 K electromagnetic background radiation.

A further desirable configuration, Big Bang Observer (BBO), would be to have several LISA-like constellations (with shorter armlengths of, say, 0.5 million km) flown simultaneously, thus providing a baseline of up to 2 AU for VLBI.

ASTROD, Astrodynamical Space Test of Relativity using Optical Devices, is the name of a Chinese space project that will, among other relativistic experiments, attempt to measure gravitational waves with armlengths of the order of 1 to 2 AU (astronomical units). It would—given similar sensitivity—be a further useful extension to yet lower frequencies in the search for and measurement of gravitational waves [10]. In Japan, a mission DECIGO with armlengths shorter than LISA's is being discussed and is, intended to bridge the frequency gap between ground-based antennas and LISA [12].

6. Technology demonstrator

Some of LISA's essential technologies (gravitational sensor, interferometry, micro-newton thrusters) are to be flight-tested on the ESA SMART-2 satellite [13].

The LISA Technology Package (LTP) on SMART-2 will contain, on a common optical bench, two gravitational sensors similar to the ones to be used in LISA proper. The relative motion between the two freely floating test masses will be monitored with high accuracy by interferometry [15]. The displacement sensitivity in this (scaled-down) experiment will come to within one power of ten to the proposed LISA sensitivity. Special attention is paid to the gravitational sensors, and their coupling to motions of the spacecraft/housing [13]. Tests of the drag-free scheme are also part of the mission and expected to run for about three months. SMART-2 is to be flown in a 'halo' orbit around the Sun–Earth Lagrange point L_1 so as to avoid the many disturbances near the Earth.

The Disturbance Reduction System, DRS, is a similar NASA package to be flown on SMART-2 [14]. It will also feature two gravitational sensors, drag-free control and laser interferometry, and correlating the results will increase the information obtained.

7. LISA data analysis

Due to the low frequency band of the LISA detection, the data rate and total amount of data are rather low. Data will be collected on board, and transmitted to Earth once every two to three days.

Nevertheless, the low transfer rate available from the spacecraft to Earth would not allow much more than the envisaged 1.5 kbit s^{-1}. Such a low data rate is, however, possible only if a moderate amount of data analysis and data reduction is done on-board.

Directivity. LISA, as in all interferometric GW detectors, has a preferred direction and a preferred polarization of the incoming gravitational wave. This would cause an antenna, fixed in space, to be sensitive in some directions and blind in others. The annual motion of LISA will, however, average out these types of directivity, as LISA will face different locations in the sky, and with different preferred polarization directions at different times. This averaging is why the sensitivity curves in figure 4 for a signal-to-noise ratio of 5 are drawn by a factor of $5\sqrt{5} = 11.2$ higher than the lower curve.

On the other hand, LISA's detection can make use of the 'signature' that continuous-wave signals will have, due to the changing response sensitivity, and due to the Doppler shifts that the signal will undergo as LISA approaches and recedes from the source during its annual orbit. A detailed analysis of the LISA sensitivity under these assumptions was made by Schilling [16, 2]. One important result was that the drastic drops in sensitivity for gravitational waves with wavelengths fitting into the armlengths are benignly smoothed out in this averaging.

Noise due to fluctuating laser frequency. The strength of the Michelson-interferometer scheme is that the high symmetry between the two arms makes the interferometer insensitive to a number of fluctuations in the illuminating light source. The most serious of these is the fluctuation in laser phase, $\delta\phi$, or in frequency, $\delta\nu$. Any change in laser frequency will cause spurious signals proportional to the difference in armlengths. The celestial mechanics of the LISA orbits will cause relative armlength variations in the order of 10^{-2}, and these would produce spurious signals from the natural laser frequency fluctuations, well above the gravitational wave signals.

Unequal-armlength interferometry. Even if the laser frequency is well stabilized to the best of current technology, perhaps to 30 Hz $\mathrm{Hz}^{-\frac{1}{2}}$, a drastic further reduction of the effect is required. Here, schemes proposed by Giampieri *et al* [17] (in the frequency domain), and then optimized with respect to the suppression of several LISA error sources [18] (in the time domain), promise significant improvement. The basic principle is to use a linear combination of the current read-out data s_i with data additionally delayed in each arm by the travel time in the other:

$$X(t) = s_1(t) - s_2(t) - s_1(t - 2\tau_2) + s_2(t - 2\tau_1),$$

where the delays τ_i are chosen to equal the true travel times T_i. It is easily verified that this algorithm can fully cancel the laser phase noise $\delta\phi(t)$.

The LISA analysis algorithms. See [18] and references therein for a detailed discussion of the merits of this *time-delay interferometry* in cancelling out not only laser phase noise, but also other instrumental errors. These form the baseline for the LISA procedure [3]. It is assumed that phase measurements are made in all three spacecraft, each equipped with independent lasers, with independent highly stable clocks (USOs), and with an intraspacecraft link between the two lasers on board each spacecraft. An extension of the method to intentional gross armlength differences is in print [19].

8. Conclusion: LISA prospects

The difficulties (and thus the great challenges) of gravitational wave detection stem from the fact that gravitational waves have so little interaction with matter (and with spacetime), and thus also with the measuring apparatus. Great scientific and technological efforts, large detectors, and a working international collaboration are required to detect and measure this elusive type of radiation. And yet—just on account of their weak interaction—gravitational waves can give us knowledge about cosmic events to which the electromagnetic window will be closed forever.

This goes for the processes in the (millisecond) moments of a supernova collapse, as well as for mergers of binaries hidden by galactic dust. Such high-frequency events (a few Hz up to a few kHz) will be accessible from the detectors on Earth. For the signals to be significant, a number of ground-based detectors should be operated in coincidence, and only such joint analyses will allow us to locate the source in the sky.

With LISA, the perspective of detecting events with non-electromagnetic radiation also holds for the distant, but violent, mergers of galaxies and their central (super)massive black holes. LISA is designed to access the low frequencies (10^{-5} Hz to 1 Hz) characteristic of such sources. The expected high signal-to-noise ratios will allow unquestionable detection with only one detector. The very significant annual 'signature' of the signal, due to the LISA orbits around the sun, will even allow us to locate the source in a narrow region of the sky.

Some of these low-frequency gravitational wave signals are guaranteed to stick out clearly from noise. Failure to observe them would cast severe doubts on our present understanding of the laws that govern the universe. Successful observation, on the other hand, would give new insight into the origin and development of galaxies, the existence and nature of dark matter, and other issues of fundamental physics [1].

A LISA follow-on mission might probe the GW background from the very beginning of our universe, as far back as 10^{-14} s after the big bang [20].

In this way, gravitational wave detection can be regarded as a new window on the universe, but to open this window, we must continue building and perfecting our GW antennas. It will only be after the large ground-based interferometers are completed (and perhaps even only after the next generation of detectors) that we will be able to record the many audio-frequency events from coalescing binaries and supernovae far beyond our own galaxy, out to hundreds of Mpc. And it is in particular when LISA is launched that we will have—in the subsonar frequencies—a sensitivity that will allow us to look far beyond that, perhaps to the very limits of the universe [21].

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