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LISA—an ESA cornerstone mission for a gravitational wave observatory

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Abstract. The European Space Agency has selected LISA, a gravitational wave observatory, as a cornerstone mission in its future science program Horizons 2000. This observatory will complement the development of ground-based gravitational wave detectors currently under construction. A spaceborne detector will enable the observation of low-frequency gravitational waves in a frequency range from 10^{-4} to 10^{-1} Hz which is totally inaccessible to ground-based experiments. This frequency range is unique in that it is expected to contain signals from massive black holes, galactive binary stars, as well as the most violent events in the Universe.

LISA will attain this low-frequency sensitivity by employing laser interferometric distance measurements over a very long baseline of 5×10^6 km. Three of these baselines form an equilateral triangle with spacecraft at each vertex. The cluster of spacecraft is in an Earth-like orbit around the Sun trailing the Earth by 20°.

The spacecraft contain infrared light-emitting Nd:YAG lasers and freely floating test masses made from a special platinum–gold alloy with vanishing magnetic susceptibility. The spacecraft are being kept centred on their test masses by using drag-free technology and field-emission electric propulsion, thus letting the test masses follow purely inertial orbits.

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1. Overview

Conceptually, the idea of implementing an interferometer in space is straightforward, but the practical realization requires an intricate blend of optical technology, spacecraft engineering and control. For a start, the interferometer mirrors cannot simply float freely in space—they must be contained inside spacecraft. Nonetheless, they can be arranged to be floating almost freely inside the spacecraft, protected from external disturbances by the spacecraft walls. As long as the spacecraft do not disturb the mirrors, ideally only gravitational waves would perturb their relative motion. 'Drag-free control' can be employed to ensure that the spacecraft always remain centred on the mirrors.

In principle, the Michelson interferometer could be realized using three spacecraft: one at the 'corner' to house the light source, beamsplitter and detector, plus one at each 'end' to house the remote mirrors. But there would be immediate practical problems with such a configuration. All three spacecraft would drift around and the corner spacecraft would not be able to keep itself aligned with both of the end spacecraft at the same time. One way around this would be to have steerable optics inside the corner spacecraft so that alignment could be maintained with the two arms independently. To avoid this complexity, LISA

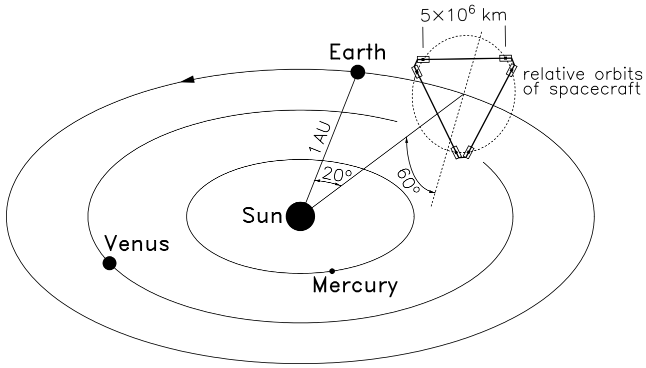

Figure 1. LISA concept. Six spacecraft in a triangle, with a pair at each vertex. Only four are required for the basic interferometry. The other two provide supplementary science information and some redundancy.

uses six spacecraft, arranged in a triangular configuration with two at each vertex. With this set-up, each of the corner spacecraft can dedicate itself to pointing at only one of the end spacecraft, thus eliminating the need to steer the main optics. The corner spacecraft must, nevertheless, communicate with each other using steerable optics—but the separation distance is so much less that the steerable components can be much smaller and hence more manoeuvrable.

Each 'corner' pair of spacecraft, separated by 200 km, is located at the vertex of a large triangle the sides of which measure 5×10^6 km in length. This arm length has been chosen to optimize the sensitivity of LISA at the frequencies of known and expected sources. A factor of 2 increase may be desirable. However, an arm length increase beyond that would begin to compromise the high-frequency sensitivity when the light in the arms experiences more than half of the gravitational wave period. An interferometer shorter than 5×10^6 km would begin to lose the interesting low-frequency massive black hole sources. It would give less scientific information but would not be any easier to build or operate because the spacecraft and the interferometry would be essentially the same.

Nominally in such an arrangement of spacecraft, any two sides of the triangle (i.e. four spacecraft) can be used for the main interferometry, with the third arm giving supplementary information and redundancy. With the six spacecraft configuration, up to two can be lost without jeopardizing the mission (as long as the two failures are not at the same corner), since the basic group of four in an approximate 'L' shape is sufficient to perform the full interferometry.

Each spacecraft is actually in its own orbit around the Sun. The six individual orbits have their inclinations and eccentricities arranged such that, relative to each other, the spacecraft rotate on a circle 'drawn through' the vertices of the giant triangle which is tilted at 60° with respect to the ecliptic. With this special choice of orbits, the triangular geometry of the interferometer is largely maintained throughout the mission. The centre of the triangle is located on the ecliptic—20° behind the Earth—and follows the Earth on its orbit around the Sun. Ideally, the constellation should be as far from Earth as possible in order to minimize gravitational disturbances. The choice of 20° is a practical compromise based on launch vehicle and telemetry capabilities.

The once-per-year orbital rotation of the LISA constellation around the Sun provides the instrument with angular resolution, i.e. the ability to pin-point the particular direction to

Figure 2. One of the six identical LISA spacecraft. The main structure is a ring with a diameter of 2.6 m and a height of 0.7 m, made from carbon-epoxy for low thermal expansion. The ring supports the payload cylinder, as shown. Equipment boxes are mounted on the outside of the ring, to house non-precision electronics (e.g. power regulator, computer, radios). FEEP control thrusters (not shown) are mounted at various locations on the outer spacecraft structure. The tops of the equipment boxes support two annular sections of solar array for power generation. A lid on top of the spacecraft (not shown) protects the thermal shields and payload cylinder from direct sunlight.

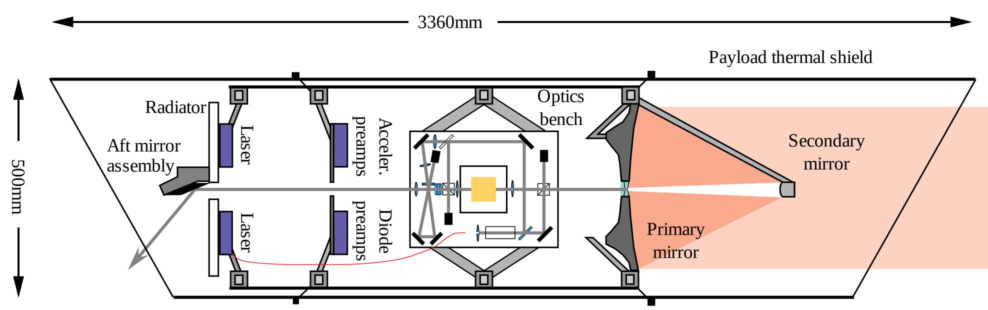

Figure 3. Cross section of the payload on each of the six identical LISA spacecraft.

(This figure can be viewed in colour in the electronic version of the article; see `http://www.iop.org/EJ/welcome`)

a source. An interferometer is rather omnidirectional in its response to gravitational waves. In one sense this is advantageous—it means that more sources can be detected at any one time—but it has the disadvantage that the antenna cannot be 'aimed' at a particular location in space. For a given source direction, the orbital motion of the interferometer Doppler shifts the signal and also affects the observed amplitude. By measuring these effects the angular position can thus be determined. This is analogous to the technique used by radio astronomers to determine pulsar locations.

It is expected that the strongest LISA sources (from very distant supermassive black holes) should be resolvable to better than an arcminute and even the weaker sources (galactic binaries) should be positioned to within 1° throughout the entire galaxy.

A LISA spacecraft is shown in figure 2 and a cross section of the payload in figure 3. Each spacecraft has its own 1 W laser (actually two, one for redundancy), its own two-mirror telescope for sending and receiving light and an optical bench which is a mechanically stable structure on which various sensitive optical components are mounted. The mirrors enclosed in each spacecraft are actually 40 mm gold–platinum cubes (also referred to as the 'proof masses'). Each one is located inside a titanium vacuum can at the centre of the respective optical bench. Quartz windows allow access for the laser light.

Within the corner pair of spacecraft, one laser is the ‘master’ and a fraction of its light (10 mW) is bounced off the back surface of its cube and sent to the neighbouring corner spacecraft (via the small steerable optics), where it is used as a reference to ‘slave’ the local laser. In this way, the main ($\sim$1 W) beams going out along each arm can be considered as having originated from a single laser. This is vital to the function of the interferometer.

The light sent out along an arm is received by the end spacecraft telescope, bounced off its cube, then amplified using its local laser, in such a way as to maintain the phase of the incoming light. The amplified light is then sent to the corner spacecraft. Amplification at the end spacecraft is required due to divergence of the beam over the very large distances. Even though each outgoing beam is extremely narrow—a few microradians—it is about 20 km wide when it reaches the distant spacecraft. This diffraction effect, together with unavoidable optical losses, means that only a small fraction of the original output power ($\sim 10^{-10}$) finally reaches the end diode. If this was simply reflected and sent all the way back, only about 200 photons per hour would reach the corner diode after the round trip. The phase signals they carry would be swamped by shot noise, the quantum-mechanical fluctuations in the arrival times of the photons. The amplification brings the number back up to over 10^8 photons/s, which makes the signal detection straightforward using standard photodiodes. The phase precision requirement for this measurement is seven orders of magnitude less demanding than is routinely achieved (at higher frequencies) in ground-based prototype interferometers.

The resulting round-trip journey from the corner to the end and back, defines one arm of the large interferometer. On its return to the corner spacecraft, the incoming light is bounced off the cube and then mixed with a fraction of the outgoing light on a sensitive photodetector, where interference is detected. The resulting brightness variations contain the phase-shift information for one arm of the interferometer. This signal is then compared (in software on the on-board computer) with the corresponding signals from the other two arms, and some preliminary data processing is done. The results are then transmitted to Earth by radio link.

The LISA spacecraft must be designed to minimize the total mass and required power. Preliminary results yield a mass per spacecraft of 300 kg and an operational power requirement per spacecraft of 192 W.

2. Lasers

Lasers have extremely narrow beams that can survive long journeys through space. In addition, they are very stable in frequency (and phase) which is crucial to interferometry since phase ‘noise’ appears just like gravitational waves. Furthermore, the infrared light has a frequency of 3×10^{14} Hz which renders it immune from refraction caused by the charged particles (plasma) which permeate interplanetary space.

The lasers for LISA must deliver sufficient power at high efficiency, as well as being compact, stable (in frequency and amplitude) and reliable. The plan is to use solid-state diode-pumped monolithic miniature Nd:YAG ring lasers which generate a continuous 1 W infra-red beam with a wavelength of 1.064 μm.

3. Drag-free and attitude control

An essential task of the spacecraft is to protect the mirrors from any disturbances which could jostle them around and create phase signals that appear as gravitational waves. For example, consider the momentum of the light from the Sun which amounts to an average pressure of about 5×10^{-6} N m^{-2}. The internal dynamics of the Sun lead to small variations—less than 1°—in this photon pressure, which occur at low frequencies within LISA's range of interest. Although this variable photon pressure may seem rather small, if it were allowed to act on the cubic mirrors, the resulting motion would be 10^4 times larger than the tiny motions due to gravitational waves that LISA is looking for.

By simply 'wrapping a spacecraft around each one', the cubes are isolated from the solar pressure—but this is not the complete picture. When the solar pressure blows on the surface of the spacecraft, it will move relative to the freely floating cube. Left alone, this motion would build up to unacceptable levels—in the extreme case, the cube would eventually 'hit the wall'. To stop this from happening, the relative motion can be measured very precisely by monitoring the change in electrical capacitance between the cube and electrodes mounted on the spacecraft. This measurement is then converted into a force command which instructs thrusters mounted on the outer structure of the spacecraft to fire against the solar pressure and keep the spacecraft centred on the cube.

This concept is, for historical reasons, known as 'drag-free control', since it was originally invented in the 1960s to shield Earth-orbiting satellites from the aerodynamic drag due to the residual atmospheric gases. The method was first demonstrated on the TRIAD spacecraft, flown by the US Navy in 1972, where the drag-free controller designed at Stanford University, in collaboration with the John Hopkins Applied Physics Laboratory, was effective in reducing the effects of atmospheric drag by a factor of 10^3. Since then, the technique has undergone continued development, most notably for use on NASA's Gravity Probe B mission, which is the proposed space experiment to search for the relativistic precessions of gyroscopes orbiting the Earth.

The thrusters used on conventional spacecraft are far too powerful for LISA. The drag-free system only needs to develop a force of a few micro-Newtons. Furthermore, the force delivered must be smoothly controllable so that the varying disturbance forces can be matched without introducing a further disturbance from the thrust system itself. Surprisingly, it is not a trivial task to build a thruster which generates such a small force and yet operates smoothly and does not consume too much power. By good fortune, ESA has been developing them for years, as an alternative to hydrazine rockets for station-keeping of communication satellites.

They are called FEEPs, for field-emission electric propulsion. They operate by accelerating ions in an electric field and ejecting them to develop the thrust.

4. Ultrastable structures

The small variations in the intensity of sunlight will cause fluctuations in the heat-load applied to the spacecraft. This could lead to thermal gradients across the optical bench, which would upset the stability of the laser cavity. To obtain the required thermal stability, most structural elements are made from carbon-epoxy which has a thermal expansion coefficient of 4×10^{-7} K^{-1} and the optical bench is made from ULE, which has a temperature coefficient at least a factor of four lower over the possible temperature range of the LISA payload. Furthermore, low-emissivity coatings are used on most surfaces inside the spacecraft and a thermal shield surrounds the payload cylinder, in order to provide isolation from the temperature variations of the spacecraft skin that is exposed to the Sun. These shields are only effective against heat fluctuations faster than a few hours to half a day. The slower variations will get through, thus making the sensitivity of LISA deteriorate rapidly below roughly 10^{-4} Hz. The use of carbon-epoxy structures also minimizes any thermally induced mechanical distortions which could produce physical changes in the optical path length, as well as local gravitational disturbances on the mirror cubes.

5. Data transmission

Each spacecraft will be equipped with two (one spare) X-band transponders with steerable 30 cm high-gain antennas for communication with the Earth. On average, the transmissions will require about 8 h per day, at a data rate of roughly 600 bits/s. The entire LISA data set, after a nominal two-year mission, will be stored on about 100 CD-ROMs.