The extreme weakness of the gravitational interaction has as one of its consequences that appreciable intensities of gravitational waves (GW) can only be generated in large size astrophysical and cosmological sources. Earth based detectors face unsurmountable problems to be sensitive to signals at frequencies below 10 Hz due to seismic vibrations. In order to see lower frequency signals, a space based detector is the natural solution. LISA (Laser Interferometer Space Antenna) is a joint ESA-NASA project aimed at detecting GWs in a range of frequencies between $10^{-4}$ Hz and $10^{-1}$ Hz, and consists in a constellation of three spacecraft in heliocentric orbit, whose GW-induced arm length variations are monitored by high precision interferometry. This article reviews the main features and scientific goals of the LISA mission, as well as a shorter description of its precursor technological mission LPF (LISA Pathfinder).

1 Introduction

The detection of gravitational waves (GW) is one of the most challenging scientific problems ever in the history of science. Ultimately, this is due to the extreme weakness of the gravitational interaction —40 orders of magnitude weaker than electromagnetism.

The nature and properties of gravitational radiation were first described by Einstein shortly after he created the General Theory of Relativity [1]. However, beyond the specific predictions of Einstein’s theory, the phenomenon of GWs appears to be an unavoidable consequence of the basic fact that no interaction can travel instantaneously from source to observer. Recall e.g. that Poisson’s equation for the gravitational potential of Newtonian gravity,

$$\nabla^2 \phi(x, t) = -4\pi G \rho(x, t),$$

where $\rho(x, t)$ is the density of matter creating the gravitational field, strongly violates such basic causality principle, and therefore needs a major conceptual reassessment. Whether this is provided by Einstein’s theory or any of its competitors —for example Brans–Dicke theory [2], see also [3]— GWs should be there, anyway. Actually, a GW detection experiment is a potential tool to decide between candidate theories.

Gravitational waves are characterised mathematically by dimensionless amplitudes $h_{\mu\nu}(x, t)$, measuring deviations from a flat space-time geometry caused by the
radiation field. Far from their sources, these amplitudes are usually very small, so the metric tensor $g_{\mu\nu}(x, t)$ splits up as

$$g_{\mu\nu}(x, t) = \eta_{\mu\nu} + h_{\mu\nu}(x, t)$$

in a quasi-Lorentzian coordinate frame, i.e.,

$$\eta_{\mu\nu} = \text{diag} \left( -1, 1, 1, 1 \right), \quad |h_{\mu\nu}(x, t)| \ll 1 .$$

Not all ten of the quantities $h_{\mu\nu}(x, t)$ contain independent information on the physics of GWs; these, as is well known from textbooks on General Relativity, have rather only two canonical degrees of freedom, usually noted $h_+$ and $h_\times$, after a universally accepted terminology, proposed by Misner, Thorne and Wheeler [4]. We recall that, for a GW travelling down the $z$-axis, the $h_{\mu\nu}$’s actually reduce to

$$h_{\mu\nu}(x, t) = \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & h_+(ct - z) & h_\times(ct - z) & 0 \\
0 & h_\times(ct - z) & -h_+(ct - z) & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}$$

Using the quadrupole approximation of General Relativity [5], one can find a crude order of magnitude estimate of the intensity of GWs far from their sources; it is given by the formula [6]

$$h \sim \frac{R}{r} \frac{v^2}{c^2}$$

where $R = \frac{2GM}{c^2}$ is the Schwarrzschild radius of the source, $v$ is a typical velocity of the matter inside it, and $r$ is the distance to the observer, assumed orders of magnitude larger than $R$. The characteristic frequency of emission is on the other hand of order $v/a$, where $a$ is roughly the linear size of the source.

The range of frequencies in which GWs happen can widely vary from $10^{-18}$ Hz, corresponding to primeval GWs, up to $10^4$ Hz or higher, corresponding to small mass BH oscillation modes. Amplitudes are however less variable, and they are very small when received on Earth, even in the best of cases. Taking into consideration the large uncertainties in their estimation, current common lore sets the amplitude range of GWs reaching the solar system somewhere in the interval

$$10^{-26} \lesssim h \lesssim 10^{-16}$$

A convenient characterisation of GW signals is in terms of their frequency spectrum. The relevance of this comes from the fact that any given detector has its own frequency window, which determines in turn which sources it will be able to sight. Figure 1 shows a very sketchy summary of source spectra, together with noise spectral densities of two interferometric detectors which will eventually see the corresponding
Figure 1: Spectral densities of noise of two very different GW detectors, \textit{LIGO} and \textit{LISA}, along with some of the signals they can sense.

signals. These detectors are \textit{LIGO}, a ground based device, and \textit{LISA}, a space borne GW telescope. A more complete description of sources is given in \textcite{7}. The most salient feature of the graph in figure 1 is the position in frequency of the sensitivity curves of both detectors, separated by 4–5 orders of magnitude.

As already stressed, detailed estimation of source amplitudes is plagued with uncertainties, due to the complicated dynamics of astrophysical systems. The cleanest systems are black hole binaries, which makes of them excellent candidates for observation. But uncertainties here are also significant, as we only have a few hints on their abundances. On general grounds, the following argument should work: since interesting GWs require large mass motions to be generated, the most intense sources will likely have low frequencies, as characteristic lengths in large mass distributions should be large, and typical time scales should therefore also be large, hence frequencies low.

To have a more quantitative idea of the orders of magnitude in this somewhat vague line of argument, let us consider the GWs emitted by the Hulse–Taylor binary...
pulsar PSR 1913+16 [8]: its orbital period is nearly 8 hours, which means it radiates GWs at a frequency of $7 \times 10^{-5}$ Hz. We shall agree that this a is rather low frequency. On the other hand, we consider that 1 kHz is a high frequency, and signals around this value are accessible with current ultracryogenic bars [9] [10] and upcoming ground based interferometers [11] [12].

The above figures are useful to make sense of what LISA is intended for: the search for low frequency GW signals in the range of $10^{-4}$ Hz to $10^{-1}$ Hz. This article will describe the reasons for this choice and the details of how LISA will be implemented. We shall first review a few basic facts about GW detection theory and then show how they apply to LISA; its sensitivity and detectable sources will also be mentioned. The technological difficulties to build a detector with the requirements of LISA have motivated the launch of a precursor mission, LPF (LISAPathfinder), and we shall also explain its objectives and how they can be accomplished. Spain has recently acquired an active role in the space borne GW detector project, whose status will be briefly summarised in the last section.

2 GW detection concepts

The weakness of the gravitational interaction shows up in a particularly dramatic form when it comes to evaluating e.g. the cross section for the absorption of GW energy by matter. If one takes for instance a solid sphere of aluminum, it can be shown [13] that the optimum cross section is

$$\sigma \simeq 10^{-24} S$$

i.e., 24 orders of magnitude smaller than the transversal area of the target body... This is not worse than the intensity of the interaction with test electromagnetic fields, see [14].

While this is at the root of the difficulties to build a working GW detector, it also has a positive counterpart: GWs are so weakly absorbed that they carry undistorted information on the interiors of the sources producing them, therefore making of GWs a unique tool for the study of such sources [7].

There are at the moment two major GW detector concepts: acoustic and interferometric detectors. The first is based on the idea of resonant amplification of the signal, see figure 2: two test masses $M$ are linked together by a spring of relaxed length $\ell_0$, so that GW tides drive their oscillations around the equilibrium position, with significant mechanical amplification at the spring’s characteristic frequency $\Omega$. The spring deformation

$$q(t) \equiv \ell(t) - \ell_0$$
thus obeys the following equation of motion\(^1\):

\[\ddot{q}(t) + \Omega^2 q(t) = \frac{1}{2} \ell_0 \ddot{h}(t),\]

(9)

where

\[h(t) = [h_+(t) \cos 2\varphi + h_\times(t) \sin 2\varphi] \sin^2 \theta,\]

(10)

and \((\theta, \varphi)\) are the angles which define the incidence direction of the GW in the laboratory frame—see a complete discussion in reference [15].

This is the main idea, but in practice acoustic GW detectors are elastic solids rather than a single spring, i.e., they do not have a single characteristic frequency but a whole spectrum. More complicated analysis tools are needed in this case to find the detector’s response—the theory is presented in full length in references [16, 17]. Currently operative acoustic GW antennas are cylindrical, but spheres are also under consideration and test [18, 19].

The second concept for GW detection is interferometry. The idea is summarised in figure 3. In order to honour theoretical rigor, a warning must be issued regarding this figure: what the interferometer really measures is a phase shift in the light travelling along two different directions, and this can be determined by solving Maxwell’s equations for a test electromagnetic travelling wave in the background geometry of

---

\(^1\)Dissipative terms are omitted at this stage, as they do not influence the key points of our present discussion.
Figure 3: The “naïve” interferometric detector concept: a GW coming perpendicular to the sheet’s plane, “+” polarised relative to the $x$ and $y$ axes, causes the end masses $M_1$ and $M_2$ to oscillate in phase opposition relative to the central mass $M_0$. Light is shone into the system, and suitable beam splitters and mirrors are attached to the masses; length changes are then measured interferometrically, which directly lead to determine the GW amplitude.

a GW, i.e.,

$$\Box A_\mu \simeq \eta^{\rho\sigma} (\partial_\rho \partial_\sigma A_\mu - 2\Gamma^\nu_{\rho\sigma} \partial_\nu A_\mu - \Gamma^\mu_{\rho\sigma} \partial_\rho A_\nu - A_\nu \partial_\rho \Gamma^\mu_{\rho\sigma}) = 0,$$  \hspace{1cm} (11)

where $\Box \equiv g^{\rho\sigma} \nabla_\rho \nabla_\sigma$, and $\nabla$ is the covariant derivative in a geometry given by (2).

The phase shift induced on a light beam travelling back and forth in a Michelson type interferometer of armlength $L$ can be found solving equations (11), and the result is \[\delta \phi = \frac{2\omega}{\Omega} h_0 \sin \frac{\Omega \tau}{2},\]  \hspace{1cm} (12)

assuming a monochromatic, “+” polarised GW of amplitude $h(t) = h_0 \sin \Omega t$, which comes in perpendicular to the interferometer plane\(^2\). Here, $\omega$ is the frequency of the light, and $\tau$ the trip time of the light in one arm, $\tau = L/c$. Formula (12) can be generalised to include arbitrary incidence directions and GW polarisations [14, 20], but the essential physics of the interferometer detector concept are already visible in this equation.

More specifically, note that, for a given GW wavelength $\lambda_{GW} = c/(2\pi \Omega)$, the phase shift is a periodic function of the the round time $\tau$. The interferometer response has thus a maximum when its armlength is $L = \lambda_{GW}/2$.

A GW of 1 kHz requires an interferometer 150 km long for correct tuning, and this is the aim of earth based detectors such as VIRGO or LIGO. These detectors are not 150 km long, but have implemented an equivalent length by a multiple reflection

\[\text{\footnotesize \textsuperscript{2}}\text{Take } \theta = \pi/2 \text{ and } \varphi = 0 \text{ in equation (10)}\]
Figure 4: Spectral density of noise for two GW detectors: in the left the narrowband device NAUTILUS, and the right the broader band system LIGO in its advanced design previsions.

procedure in the mirrors whereby light beams actually interfere after they have travelled the arms back and forth a suitable number of times. Their actual armlength is only 3 or 4 km.

2.1 GW detector sensitivities

The above considerations refer only to fundamental properties of GWs and their interactions with light beams and matter. But a real detector behaves according to no less fundamental laws regarding the structure of matter and light. These include the presence of noise sources which unavoidably degrade their sensitivity, and set limits on the intensity of the GWs they can possibly see.

By way of example, the plots in figure 4 show the sensitivities, expressed in spectral density of noise, of two very different GW detectors: one is the ultracryogenic bar NAUTILUS, sitting in INFN Laboratories in Frascati, near Rome, and the other is the long baseline (4 km) LIGO. The first is a narrowband device, as can be seen in the plot, which has two resonant frequencies\(^3\). Due to fundamental reasons, the best bandwidth which can be possibly attained with this device is some 20 Hz, the distance between the two resonant peaks, as also shown in the graph. On the other hand, see right panel in figure 4 an interferometric detector, such as LIGO, has a wider sensitivity band, a few 100 Hz.

Wider bandwidth is obviously a significant improvement, as more information from the source is made available with it. Earth based detectors do however face

\(^3\)This is due to the readout system, based on a resonant transducer, which causes a split up of the fundamental mode of the cylinder, otherwise in the middle of the two lines seen.
an insurmountable sensitivity barrier: it is the so called seismic wall—see again right panel in figure 4—caused by the vibrations of the ground, which cannot be sufficiently damped at frequencies below some $10^{-50}$ Hz [22]. In addition, going to lower frequencies requires stretching the interferometer arm length, eventually to prohibitive values.

Both requirements—no seismic wall and long arm lengths—find a natural solution in a space-borne GW antenna. This is the idea behind the LISA Project.

3 LISA

LISA (Laser Interferometer Space Antenna) is a joint ESA–NASA Project. It was formally approved by ESA’s Science Programme Committee in November 2003 as a Fundamental Physics mission to fly in 2012. The Project was also favourably informed by an independent Technology Readiness and Implementation Plan assessment panel in April 2003 for NASA. Financial contribution to LISA is currently envisaged as 50% from each side of the Atlantic.

The idea of placing a GW detector in space dates back to the mid 1980’s, and first designs were developed by various American scientists. None of such proposals was however approved for actually flying in a NASA mission. In 1993 focus shifted to Europe, and after several studies LISA eventually became the actual space-borne GW detector. NASA decided to join the Project in 1998 [23].

In the following sections we give a brief summary of the main design and scientific characteristics of LISA as they stand at the time of writing. References will be provided for more detailed understanding of the interested reader, and too technical material will be omitted. In page 15 a short mission summary is also given.

3.1 LISA concept

LISA is conceived as an interferometric detector to be sensitive to GWs in the range of sub-milli-Hertz frequencies. As already discussed in section 2.1 this requires suitably long arm lengths. In the case of LISA this will be five million kilometres, which sets the resonance frequency in a few mHz.

The interferometer baseline configuration can be seen in figure 4: three spacecraft host two freely falling test masses each, and form an equilateral triangle, $5 \times 10^6$ km to a side. Incoming GWs cause distances between pairs of masses to change, and the changes are tracked by interferometry between laser light beams travelling along the three arms of the configuration. The interference generation scheme is however not the usual one (e.g., Michelson) but rather an active one, based on transponders instead of mirrors. Details will be given in section 3.4 below.
3.2 Scientific goals of LISA

The sensitivity of LISA is limited by various sources of noise which happen in the frequency band around 1 mHz. This is represented in figure I left curve. In the lower part of the spectrum, sensitivity is limited by signal loss because the resonant armlength exceeds the interferometer’s, and also because of internal sources of noise associated with various measuring instruments, temperature gradients, etc. In the resonance region, shot noise is the main source of disturbances: interferometric measurements are made by means of photodiodes, and these are subject to quantum fluctuations which tend to mask low level signals. Finally, at higher frequencies signals periodically cancel out due to nodes in the interferometer response —see equation (12)—, and shot noise increases, too.

If the foreseen sensitivity is reached, LISA will be able to see a number of very interesting sources, such as mergers of large black holes or even GW backgrounds, see [7] for a rather complete enumeration. Unfortunately, galactic binaries are estimated to produce a background GW luminosity in a part of LISA’s sensitivity band which will tend to conceal individual events, unless they are very bright. This is represented in figure II by the shaded area labeled “unresolved galactic binaries”, and it
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Table 1: The assured galactic sources of LISA.

| Class      | Source          | d/pc | $f$/mHz | $M_1/M_\odot$ | $M_2/M_\odot$ | $h/10^{-22}$ |
|------------|-----------------|------|---------|---------------|---------------|--------------|
| WD+WD      | WD 0957-666     | 100  | 0.38    | 0.37          | 0.32          | 4            |
|            | WD 1101+364     | 100  | 0.16    | 0.31          | 0.36          | 2            |
|            | WD 1704+481     | 100  | 0.16    | 0.39          | 0.56          | 4            |
|            | WD 2331+290     | 100  | 0.14    | 0.39          | >0.32         | >2           |
| WD+sdB     | KPD 0422+4521   | 100  | 0.26    | 0.51          | 0.53          | 6            |
|            | KPD 1930+2752   | 100  | 0.24    | 0.50          | 0.97          | 10           |
| Am CVn     | RXJ 0806.3+1527 | 300  | 6.2     | 0.4           | 0.12          | 4            |
|            | RXJ 1914+245    | 100  | 3.5     | 0.6           | 0.07          | 6            |
|            | KUV 05184-0939  | 1000 | 3.2     | 0.7           | .092          | 0.9          |
|            | AM CVn          | 100  | 1.94    | 0.5           | .033          | 2            |
|            | HP Lib          | 100  | 1.79    | 0.6           | 0.03          | 2            |
|            | CR Boo          | 100  | 1.36    | 0.6           | 0.02          | 1            |
|            | V803 Cen        | 100  | 1.24    | 0.6           | 0.02          | 1            |
|            | CP Eri          | 200  | 1.16    | 0.6           | 0.02          | 0.4          |
|            | GP Com          | 200  | 0.72    | 0.5           | 0.02          | 0.3          |
| LMXB       | 4U 1820-30      | 8100 | 3.0     | 1.4           | <0.1          | 0.2          |
|            | 4U 1620-67      | 8000 | 0.79    | 1.4           | <0.03         | 0.06         |
| W UMa      | CC Com          | 90   | 0.105   | 0.7           | 0.7           | 6            |

can be compared to the sun’s day lihgt, which prevents the observation of stars and planets in the optical frequency band. Even so, a number of galactic sources, whose properties are known from electromagentic observation, are actually guaranteed to be seen by LISA if it works as planned. An updated list of such sources is shown in table 1. They fall in the area labeled “resolved galactic binaries” in figure 1.

3.3 Orbits

A crucial requirement for LISA to work is of course that the test masses be in free fall. Within the solar system, this means that the three spacecraft should follow a geodesic motion determined by the gravitational field of the Sun and the planets. At the same time, such motion must be sufficiently stationary to ensure that relative distances between spacecraft do not undergo variations which could be wrongly taken as caused by real GWs, or which may conceal them.
After some initial debate, it was agreed that LISA should be placed in a heliocentric orbit, rather than geocentric. It is however a non-trivial problem to find a flight configuration which meets the requirements of stationarity and suitability for LISA. Analyses by Bender, Folkner and others [24, 25] resulted in a series of remarkable conclusions which are schematically summarised in figure 6.

The baseline configuration is, as already stated, an equilateral triangle $5 \times 10^6$ km to a side. The barycentre of the triangle follows the ecliptic, and the plane of the triangle is inclined $60^\circ$ with respect to the ecliptic plane at any given time; however its normal does not point to a fixed position in the sky, but rather describes a cone around the normal to the ecliptic, a complete tour per year. Each of the three satellites revolves around the Sun in a nearly circular orbit of eccentricity 0.01, inclined $1^\circ$ relative to the ecliptic, while the triangle itself rotates counterclockwise about its barycentre, also with a period of one year. Finally, the barycentre trails $20^\circ$ behind the Earth, a figure which, unlike the just quoted astrometric parameters, is not dynamically fixed, but a compromise between telemetry constraints (satellites not too far) and Earth-Moon perturbations (satellites not too near).

The reader may wonder at this stage about the stationarity of this configuration, the more so given that LISA is supposed to perform nano-meter laser interferometry: is it even conceivable that the spacecraft keep their relative distances to within $10^{-9}$ metres?

The answer to this question is obviously “no”, but it must be admitted that such question does not really address a relevant issue for LISA... Figure 7 shows how relative distances between the three satellites vary over a period of 10 years,
Figure 7: Variations of the relative distances between the three pairs of spacecraft of LISA. Estimates correspond to a period of ten years from January 1st 2010, around the time of flight of the mission. As can be seen, maximum variations are about 50,000 km, only a 10% of the nominal arm length of $5 \times 10^6$ km.

the (extended) scheduled mission lifetime, from January 1st 2010 onwards. Dates of course affect calculations, due to solar system ephemeris. The plot shows that distance variations can be as large as 50,000 km, 10% of the baseline arm length of $5 \times 10^6$ km. The relevant datum however is that variation periods are in the order of a few months, well below the frequency sensitivity range of LISA, which corresponds to periods of only hours. This means that fluctuations of the latter period happen against a comparatively very stable background baseline distance, which is well known at any given time. In summary, if LISA is quiet enough at $10^{-4} - 10^{-3}$ Hz then the possibility of sensing GWs in that frequency band may not be disturbed by solar system induced arm length fluctuations.

Placement of the satellites in the initial coordinates and orientations is aided by star trackers, working in conjunction with detailed star databases. The laser itself is of course an essential pointing resource. Micro thrusters take care of final adjustment.
3.4 Interferometry

The interferometry in LISA has some differences with that in earth based GW detectors, which are essentially Michelson, the most important being related to the way light beams are made to interfere.

In LISA, like in earth based detectors, the laser source is a Yag Neodimium laser head, 1 watt effective power, which emits in a stable infrared wavelength of 1.064 microns. The beam divergence is small, $4 \times 10^{-6}$ radians. Nevertheless in the case of LISA the light must travel 6 million kilometres before it reaches the other end mass, which means the light power is spread over a circular spot of about 20 km in diameter at that distance. Only a small fraction of this power is collected by the receiver, actually $10^{-10}$ watts. If this were reflected back to the emitter’s location then only some 200 photons per hour would be available for interference... This is by far much less than the photon counting noise in the sensitive photodiodes, so the experiment would be impracticable.

The solution to this difficulty is the use of active mirrors, or transponders: in the receiving satellite a new laser source is installed which is phase locked to the incoming light, and shone back to the origin. On reception of two such signals from the two remote satellites, a phase comparison (interference) is possible which reveals any relative displacements between the test masses.

In practice, the laser light is modulated by means of acousto-optical modulators (AOM). These are non-linear devices which alter the frequency of the light in a controlled way, shifting it by some 100 MHz. The main beam is split into two, and these are frequency shifted by two different AOMs to frequencies which differ by about 1 kHz, the so called heterodyne frequency. In the end the signal will be sought in the heterodyne modulated component, so that the valuable information signal can be analysed at low frequencies —see [26] for a thorough description.

3.5 Inertial sensors and Drag free

A most delicate problem in LISA is to make sure that the test masses do actually follow geodesic motions to very high precision. Interplanetary space is in fact a considerably hostile medium: solar radiation pressure, ionising particle fluxes, and environmental magnetic fields are among the agents which would perturb geodesic motion should the test masses be floating unshielded in their orbits.

Apart from hosting the measuring and control instrumentation, the spacecraft play a fundamental role in providing the test masses adequate protection against external agents. Test masses are freely floating inside the spacecraft, and it is therefore the latter which receive the impact of perturbations, eventually being driven away from their geodesics. In order not to drag along the test masses with it, a so called drag free system is implemented in the satellites: this consists in an inertial sensor
and an associated actuation system.

Each test mass is housed in a box whose walls are metallic plates which form capacitors with the faces of the test mass itself. In equilibrium conditions the mass is centred in the housing, and deviations thereof result in capacity changes, which are detected by corresponding bias voltage variations [27]. This is called inertial sensor (IS). Its error signal is then used to send suitable ignition commands to a set of FEEP (Field Emission Electric Propulsion) micro-thrusters which restore the centred position of the test masses by acting on the spacecraft only. The FEEP’s produce very delicate micro-newton forces by the ejection of ions, accelerated in a several kilovolt electric field [28].

3.6 LISA mission summary

Figure 8 shows a few details of the structure of the spacecraft and the science module it hosts. Thermal stability is a major requirement, as thermal gradients affect both the interferometry and the IS. The solar panels partly stabilise the temperature, which should be about 300 K, but additional thermal shields are necessary for fine tuning. Telescopes are needed both for sending light to remote spacecraft, and to collect incoming light from them; they are Cassegrain type, with a parabolic primary mirror of 300 mm diameter and a secondary of 32 mm.

The science module is a Y-shaped tube with (obviously) a separation of 60°, and it includes all the elements described above. In order to prevent sunlight from getting into the system, the ends of the Y carry 30° baffles. Aligned with them star trackers are attached for coarse pointing operations. All together each spacecraft has a diameter of 3 metres, and weighs 274 kg.

The table in page 15 presents a summary of various parameters of the mission.

![Figure 8: Left: view of each of the three LISA spacecraft. The top lid (solar panel) is shown cut to see the interior. Right: detail of the main parts of the science module.](image)
**LISA Mission Summary**

| **Objectives:** | Detection of low-frequency ($10^{-4}$ to $10^{-1}$ Hz) gravitational radiation with a strain sensitivity of $4 \times 10^{-21}/\sqrt{\text{Hz}}$ at 1 mHz.
Galactic binaries (neutron stars, white dwarfs, etc.); extra-galactic targets are supermassive black hole binaries (SMBH-SMBH and BH-SMBH), SMBH formation, and cosmic background GWs. |
| **Payload:** | Laser interferometry on six-degree-of-freedom capacitive sensing drag-free reference mirrors, housed in 3 spacecraft; arm lengths $5 \times 10^6$ km.
Each spacecraft has two lasers (plus two spares) which operate in a phase-locked transponder scheme.
Diode-pumped Nd:YAG lasers: wavelength 1.064 µm, output power 1 W, Fabry-Perot cavity for frequency-stability of 30 Hz/$\sqrt{\text{Hz}}$.
Quadrant photodiode detectors with interferometer fringe resolution, corresponding to $4 \times 10^{-5} \lambda/\sqrt{\text{Hz}}$.
30 cm diameter f/1 Cassegrain telescope (transmit/receive), $\lambda/10$ outgoing wavefront quality.
Drag-free proof mass (mirror): 40 mm cube, Au-Pt alloy of low magnetic susceptibility ($< 10^{-6}$); Titanium housing at vacuum $< 10^{-6}$ Pa. |
| **Orbit:** | Each spacecraft orbits the Sun at 1 AU.
Spacecraft distributed at three vertices, defining an equilateral triangle with a side length of $5 \times 10^6$ km (interferometer baseline).
Triangle rotates about its centre once a year. Centre follows ecliptic, 20° behind the Earth. |
| **Launcher:** | Delta II 7925 H, 10 ft fairing, housing a stack of three composites consisting of one science and one propulsion module each.
Each spacecraft has its own jettisonable propulsion module to provide a $\Delta V$ of 1300 m/s using solar-electric propulsion. |
| **Spacecraft:** | 3-axis stabilized drag-free spacecraft (three)
*mass: 274 kg each spacecraft in orbit
*propulsion module: 142 kg one module per spacecraft
*propellant: 22 kg for each propulsion module
*total launch mass: 1380 kg
*power: 940 W each composite during cruise
*power: 315 W each spacecraft in orbit
Drag-free: $3 \times 10^{-15}$ m/s² (rms) in the band $10^{-4}$ to $3 \times 10^{-3}$ Hz, achieved with 6×4 Cs or In FEEP thrusters
Pointing: few nano-rad/$\sqrt{\text{Hz}}$ in the band $10^{-4}$ Hz to 1 Hz
Payload mass/power: 70 kg/72 W each spacecraft |
| **Science data rate:** | 672 bps all three spacecraft |
| **Telemetry:** | 7 kbps for about 9 hours inside two days |
| **Mission Lifetime:** | 2 years (nominal), 10 years (extended) |
4 The LISA Pathfinder mission

LISA technological requirements are extremely demanding indeed. One of the greatest difficulties to get it working is to ensure that the drag free subsystem works properly. Drag free systems have been used in many missions since the 1960’s, when they were first introduced to compensate for height loss in low geocentric orbit satellites, caused by rarified atmospheric gas friction —hence the name drag free. Improvement has been enormous since, but the best technology tested so far is still orders of magnitude away from the needs of LISA.

Because of the high risk of launching a very expensive mission whose technology is not sufficiently verified, ESA decided that a previous, smaller mission should be flown first to ensure proper technology readiness. This mission is SMART-2 (Small Mission for Advanced Research Technology number 2), now renamed as LISA Pathfinder (LPF)\textsuperscript{4}. LPF will carry on board the LTP (LISA Test-flight Package), the payload which incorporates the technology to be tested.

LPF is scheduled for launch in late 2007, five years before LISA—provided of course the test is successful. This is a technological mission, so it is not intended to measure any GWs. Its very high precision distance measurements, however, have already prompted ideas to consider potential applications of the analysis of its data stream [29]. In the following sections we give a summary description of the main elements and functions of the LTP and the test.

4.1 LPF mission concept

One of the most demanding requirements of LISA, as already stressed in section 3.5, is the drag free subsystem. In terms of spectral density of noise, the LISA goal sensitivity is

\[
S_h^{1/2}(\omega) \leq 4 \times 10^{-21} \left[ 1 + \left( \frac{f}{3 \text{ mHz}} \right)^2 \right] \text{Hz}^{-1/2}, \quad 0.1 \text{ mHz} \leq \frac{\omega}{2\pi} \leq 0.1 \text{ Hz} \tag{13}
\]

This can be easily translated into relative acceleration noise by means of the following considerations. Like in (9), the GW relative acceleration between two test masses is given in terms of the amplitude \( h(t) \) by \( \Delta a_{\text{GW}} = L \dot{h}/2 \), where \( L \) is the rest distance between them. If non-GW forces, \( \Delta F \), are also present —essentially non-wished, random perturbations— then the total acceleration is, clearly,

\[
\Delta a \equiv \frac{d^2 \Delta x}{dt^2} = L \frac{d^2 h}{dt^2} + \frac{\Delta F}{m} \tag{14}
\]

\textsuperscript{4}Initially, SMART-2 was planned to also fly a technology test for the mission DARWIN, but this was dropped and SMART-2 is currently a LISA only mission.
where $m$ is the mass of one test mass. It is expedient to rewrite this expression in frequency domain:

$$\widetilde{\Delta a}(\omega) = -\omega^2 \widetilde{\Delta x}(\omega) = -L\omega^2 \widetilde{h}(\omega) + \frac{\widetilde{\Delta F}(\omega)}{m}$$  \hspace{1cm} (15)$$

where a tilde ($\tilde{}$) stands for Fourier transform. If we now take spectral densities in the last equation we find, assuming of course that the the true GW signal is deterministic, that the spurious forces $\Delta F$ actually fake a GW noise with equivalent spectral density (rms)

$$S_{h}^{1/2}(\omega) = \frac{S_{\Delta F}^{1/2}(\omega)}{mL\omega^2}, \quad \text{equivalent signal} \hspace{1cm} (16)$$

In terms of acceleration noise of the test masses, the top level requirement for LISA, equation (13), can be rewritten as

$$S_{a}^{1/2}(\omega) \leq 3 \times 10^{-15} \left[1 + \left(\frac{f}{3 \text{ mHz}}\right)^2\right] \frac{m}{s^2 \sqrt{\text{Hz}}}, \quad 0.1 \text{ mHz} \leq \frac{\omega}{2\pi} \leq 0.1 \text{ Hz}, \quad \text{LISA}$$  \hspace{1cm} (17)$$

The LTP concept is to squeeze two LISA test masses into a small satellite and check for drag free performance between these —figure 9 the $5\times10^6$ km of a LISA

![Figure 9: Conceptual diagramme of LTP. GRS stands for Gravitational Reference Sensor, or Inertial Sensor in the jargon of this paper.](image)
arm is thus compressed to a much shorter distance of some 30 centimetres. It has been agreed that performance of LTP can be considered satisfactory if the requirement for LISA is relaxed by one order of magnitude, both in spectral density of noise and in frequency band. More specifically, \[ S_1^{1/2}(\omega) \leq 3 \times 10^{-14} \left[ 1 + \left( \frac{f}{3 \text{ mHz}} \right)^2 \right] \frac{m}{s^2 \sqrt{\text{Hz}}} \quad 1 \text{ mHz} \leq \frac{\omega}{2\pi} \leq 30 \text{ mHz}, \quad \text{LTP} \]

\[ S_1^{1/2}(\omega) \leq 3 \times 10^{-14} \left[ 1 + \left( \frac{f}{3 \text{ mHz}} \right)^2 \right] \frac{m}{s^2 \sqrt{\text{Hz}}} \quad 1 \text{ mHz} \leq \frac{\omega}{2\pi} \leq 30 \text{ mHz}, \quad \text{LTP} \]

4.2 Philosophy of the test

The instrumentation and design of the LTP must ensure that any residual accelerations, i.e., those of unknown physical origin, be below the requirement expressed by equation (18). This requires in turn a detailed apportioning of different contributions to the background noise.

An essential fact in this respect is the following: certain perturbing agents couple the spacecraft structure to the test masses, while others are independent of them. A sort of master equation can thus be set up:

\[ a_{\text{noise}} = \frac{F_{\text{int}}}{m} + \omega_p^2 \left( x_n + \frac{F_{S/C}}{M\omega_{fb}^2} \right) \]

(19)

with the symbols meaning:

- $F_{\text{int}}$: Total random force acting on a given test mass, independent of its position at any given time.
- $\omega_p^2$: Elastic constant (or stiffness) of coupling between the test mass and the spacecraft. This may be a negative number, if the equilibrium position is unstable relative to the considered deviation.
- $x_n$: Random displacement fluctuations of the test mass.
- $F_{S/C}$: Random force fluctuations acting on the spacecraft which back act on the test masses through the drag free actuation.
- $\omega_{fb}^2$: Elastic constant of the above coupling. This is of course related to the response time of the actuation system.
- $M$ is the spacecraft mass, and $m$ is the test mass mass.

All the parameters in (19) must be evaluated on the basis of experimental measurement, and to this end several measuring runs and operation modes have been designed. In each case, the LTP interferometer will be used as a diagnostic instrument, as its foreseen sensitivity is largely sufficient to meet the measurement demands.
Figure 10: Left: the Lagrange points of the Earth-Sun system; LPF will go to L1. Right: engineering schematics of the LTP; the cylindrical towers on the ends host the inertial sensors, and the platform in between is the optical bench.

necessary to establish the validity of the limit set by equation (18). The description of further technical details is beyond the scope of this article, but information can be found in the References section below.

4.3 LPF mission summary

The LPF mission will be placed in a Lissajous orbit around the Lagrange point L1 of the Earth-Sun system, some 1.5 million kilometres from here —figure 10 left. Launch date is forseen for late 2007, and it will take the satellite some three months to reach the operations destination. The various LTP tests are scheduled to last 100 days, 23 of which will be in joint operation with DRS (Disturbance Reduction System)
. The DRS will require another 100 day period of tests, so the whole mission lifespan is about a half year.

Some of the internals of the LTP core are shown in figure 10 right. The green towers on either side host the inertial sensors and the caging mechanism, a mechanical system which holds the test masses fixed during launch and then releases them for operation. Optical fibres (in red) are connected to the towers to let ultraviolet light get into the IS for eventual electrical discharge by photoelectric effect: this is necessary as cosmic rays and solar flares deposit charge in the IS and degrade its performance. Between the towers lies the optical bench with all its mirrors, beam-

5DRS is a second technological payload, indepenently developed for LISA by NASA scientists and engineers. It will also be flown on board LPF, an ESA alone mission.
splitters and photodiodes, necessary for the various interferometric measurements. The optical bench is manufactured with a low thermal coefficient of dilatation to ensure stability, and the optical elements are bonded to it rather than glued, for the same reason. The optical bench is tied to the ISs by means of vertical glass panels, as shown.

The entire apparatus is placed inside a double layer thermal shield —not shown in the figure— which affords thermal insulation and a mechanical interface with the spacecraft. The laser head is placed outside the latter, but inside the spacecraft, and the light is fed in by means of optical fibres, too. The electronics boxes are placed outside as well to reduce heating and interference effects.

4.4 The Spanish role in LPF

An important part of the LTP is the so called diagnostics subsystem. This consists in a number of sensors which are meant to monitor various perturbations affecting the scientifically relevant measurements. More specifically, the diagnostics subsystem must monitor

- Thermal gradients across the IS
- Electric charge accumulation in the test masses due to the impact of ionising particles in cosmic rays and solar flares
- Magnetic field gradients across the IS
- Solar radiation pressure fluctuations

The appropriate sensors need to be programmed and controlled, and this is done by means of the Data Management Unit (DMU), which also hosts various service electronics, and post-processes the main science data stream coming from the interferometer.

The international consortium of the LTP offered the responsibility of the design, manufacture and integration of both the diagnostics subsystem and the DMU to a Spanish group, which is in the Institut d’Estudis Espacials de Catalunya (IEEC), in Barcelona. This happened in early 2003, after a larger collaboration had been set up a year earlier to get into the scientific teams of LISA. That group includes IEEC, two Universities from Barcelona (UB and UPC), the Consejo Superior de Investigaciones Científicas, and the Universities of Valencia and Alicante. The collaboration is currently active and looking into the longer term future of the GW detection Project. During 2003, the Barcelona part of the team was consolidated as a technological partner in LPF, and has made industrial contacts to develop the engineering parts of its assigned tasks. A significant project proposal was submitted to the Spanish National Space Programme (PNE) in December 2003, and at the time of writing the report of the review process is underway. The contribution by Miquel Nofrarias
in this Proceedings book reports on progress being made on the issue of thermal diagnostics.

5 Conclusions

The 21st century is witnessing an unprecedented scientific effort aiming at the explicit detection of GWs. The first endeavours in this direction date back to the 1960’s, after pioneering work by Joseph Weber. Progress has been enormous since, thanks to the dedication of two generations of scientists. The new large interferometric detectors (VIRGO, LIGO, TAMA, GEO-600) are close to reaching full performance, and they could well see GWs for the first time within the next few years. LISA is scheduled to fly in 2012, so it fully joins the course of events in this world-wide scientific programme.

There are however two very specific characteristics of LISA which make a qualitative difference with earth based GW antennas: one is its frequency range, around one milli-Hertz, and the other is that LISA is guaranteed the sighting of GW signals from a score of galactic sources.

LISA is an expensive and difficult Project, as shown in this article. In particular, technology readiness is a real issue, and this is why LPF is programmed to fly first. Prospects however look good, as hard work by many scientists, engineers and institutions continues to be done with considerable devotion. This has resulted in unanimous approval of the mission by ESA’s Space Programme Committee in November 2003. In summary, LISA is a major challenge, but truly valuable science outcome from it appears to be a sound prospect.

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