Milli-Hertz Gravitational Waves: *LISA* and *LISA PathFinder*

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**Abstract.** Ground based GW detectors are limited at their lower frequency band (1–10 Hz) by settlement gravity gradients and seismic noise, and their sensitivity peaks at around 100 Hz. Sources in this band are mostly short duration signals, and their rates uncertain. Going down to milli-Hertz frequencies significantly increases the number and types of available sources. *LISA* was planned with the idea to explore a likely richer region of the GW spectrum, beyond that accessible to ground detectors; the latter are however expected to produce the first GW observations. In this paper I will present the main *LISA* concepts; in particular, emphasis will be placed on *LISA PathFinder*, the ESA precursor of *LISA*, in which our research group in Barcelona is heavily involved.

1. **Introduction**

In the classical Newtonian theory of Gravity, gravitational fields do not propagate away from their sources, they rather instantly spread across the surrounding space out to infinite distances. This is of course incompatible with the causality principle set out in Einstein’s Special Relativity
Theory [1], i.e., that there is no possibility that either energy or matter travel at speeds higher than the speed of light, c. Obviously, gravitational fields carry energy, hence they may not propagate to remote places instantly. The existence of Gravitational Waves (GW), or some sort of radiation gravitational field, must therefore exist in Nature if the causality principle, as stated above, is to hold true.

Einstein described GWs for the first time shortly after he completed his General Relativity theory [2]. He found that, according to his theory, GWs are small perturbations in the space-time geometry which, in an otherwise flat (Lorentz) space-time, travel at the speed of light. He also found they have quadrupole structure with only two polarisation degrees of freedom. Finally, he gave (approximate) formulae for the GW amplitudes and the energy loss rate to gravitational radiation by mechanical systems.

Strong confidence in Einstein’s General Relativity theory predictions, endorsed by every piece of experimental and observational evidence so far, is a good motivation to search for GWs. Although this is of course a weak scientific argument, it did encourage the first research efforts to detect GWs. In 1974 the announcement by Russell Hulse and Joseph Taylor of the discovery of the binary pulsar PSR B1913+16 was meant to change the status of GWs from a theoretical conjecture into a real physical phenomenon. Later on, in 1993 Hulse and Taylor were awarded the Nobel Prize of Physics “for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation”; this indeed included the radiation of GWs from the binary system, hence we no longer need the above confidence argument to advocate the interest of GW detection research... 

PSR B1913+16 was tracked until 2006, when the timing measurement precision reached the confusion limit with other noise sources —see reference [3] for technical details. The GW radiation effect is inferred from the secular shrinkage of the pulsar’s orbit, normally expressed in the equivalent term of orbital period decay. This is seen to proceed, year after year, with an ever increasing coincidence with the predictions of General Relativity, the latest result [3] being that

\[
\frac{\dot{P}_{\text{measured}}}{\dot{P}_{\text{theory}}} = 0.997 \pm 0.002
\]

i.e., theory and observations match to around 0.1% —a remarkable figure.

Quite a few other binary pulsars have been discovered since 1974, and all of them have proved to be the excellent gravity laboratories they were foreseen to be, in particular as regards the confirmation that binary systems emit gravitational radiation —see [4] for a review.

Table 1 provides a number of interesting parameters of the Hulse and Taylor binary pulsar. Let us consider a few consequences which will be useful further down in this review.

| Character      | Parameter                        | Value                        |
|----------------|----------------------------------|------------------------------|
| **Keplerian**  | Orbital period                   | \(P = 0.322997448930 (4)\) days |
|                | Eccentricity                     | \(e = 0.6171338 (4)\)        |
|                | Projected semi-major axis        | \(a \sin i = 2.3417725 (8)\) light-sec |
| **Post-Keplerian** | Periastron precession          | \(\langle \dot{\varphi} \rangle = 4.226595 (5)\) deg/year |
|                | Time dilation + grav redshift    | \(\gamma = 0.0042919 (8)\) sec |
|                | Orbital period decay             | \(\dot{P} = -2.4184 \times 10^{-12}\) |
| **General Relativity** | Pulsar mass          | \(m_p = 1.4414 (2) M_\odot\) |
|                | Companion mass                   | \(m_c = 1.3867 (2) M_\odot\) |
|                | Orbit inclination                | \(\sin i = 0.73 (4)\)        |

Table 1. PSR B1913+16 parameters (drawn from reference [3])
As already mentioned, General Relativity is strongly endorsed by the accuracy with which the results of experiments/observations match to this date its theoretical predictions. Concerning the binary pulsar, we can use the data in table 1 and the equations of General Relativity to infer the following for PSR B1913+16:

| Parameter                        | Value         |
|----------------------------------|---------------|
| GW emission frequency           | $f \sim 70 \mu$Hz |
| Current GW emission amplitude    | $h \sim 2 \times 10^{-23}$ |
| Estimated lifetime               | $\tau \sim 300$ million years |

As we see, the GW emission happens at a very low frequency and with a very tiny amplitude. Nevertheless, as the binary loses energy to GWs, these two parameters (frequency and amplitude) grow, while the system size shrinks until the stars eventually merge in about 300 million years. Since this figure is much less than the age of the Universe, one reasonably expects that many other binaries exist which are older than PSR B1913+16, hence that they have entered the frequency band and sensitivity range of operating GW detectors and can be seen.

Since this review is about milli-Hz GW detection, the above gives at least an indicative idea of where GWs can surely be found. In the following sections we will present LISA, the first space-borne GW detector, and its expected scientific yield, i.e., the foreseen (and unforeseen) GW sources emitting at frequencies around 1 milli-Hz, a band where many are expected. We will also address briefly LISA PathFinder the technological precursor of LISA, in which we are involved.

2. The LISA concept and scientific scope

LISA (Laser Interferometer Space Antenna) is based on the same working principles as e.g. VIRGO and LIGO: a passing gravitational wave causes a distortion of the geometric properties of the space-time region it sweeps; electromagnetic waves circulating across that region are indeed also affected by the GWs, and this happens in the form of phase shifts. For example, the phase a beam of light at point $B$ travelling from point $A$, say, is different if there is or there is not a GW in the intervening space. This fact can be taken advantage of to measure such phase shifts by interferometry, thence to detect GWs $[5]^1$.

If laser links are established between pairs of masses which are in (nominally) pure geodesic motion, at least along the directions of the links, then phase shifts in the laser beams can be compared after the light is reflected in the remote masses and recombined in their origin by optical interferometry. This is how LIGO and VIRGO work, and also how LISA works—except that the latter has specific requirements due to its much larger size, and to its being in space. According to the theory $[5]$, the phase shift difference between the interfering beams as they recombine after their round trips up and down the respective interferometer arms is

$$\delta \phi(t) \propto h(t) \sin \left( \frac{\Omega_{GW} L}{c} \right) \quad (2)$$

where $h(t)$ is the amplitude of the incoming GW$^2$, $\Omega_{GW} = 2\pi f_{GW}$ its angular frequency, $L$ the interferometer arm-length and $c$ the speed of light in vacuum; the GW is assumed to impinge perpendicularly on the interferometer plane. The proportionality factor depends on the angle between the interferometer arms, and the signal is maximum when this angle is 90°. A clear

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$^1$ This is more often worded in terms of the GW changing the distance between the points $A$ and $B$, but the final result, i.e., how is the signal seen in the interferometer, is the same.

$^2$ Actually a combination of $h_\perp(t)$ and $h_\parallel(t)$ depending on the angles between the GW’s axes and the laboratory axes.
Figure 1. *LISA*’s equilateral triangle configuration. The distance between each pair of spacecraft is 5 million kilometres, which corresponds to a GW frequency of 15 milli-Hz — see equation (3). Each spacecraft houses two proof masses in nominally geodesic motion (free fall), and the relative distance variations in a frequency band around 1 mHz between corresponding proof masses in remote spacecraft is measured to picometre precision by means of laser interferometry.

and important consequence of equation (2) is that a maximum signal is obtained when the arm-length is tuned to the GW’s wavelength as\(^3\)

\[ L = \frac{\lambda_{GW}}{4} \]  

(3)

This means if we want to optimise a detector for e.g. 1 kHz signals we need interferometer arms of 75 kilometres. This can be reduced by use of a multiple reflection system (or, equivalently, Fabry-Perot optical cavities), which can make sensitive detectors at 100 Hz with only 3–4 kilometre arm-lengths [6].

Astrophysical sources in lower frequency bands appear more likely, as powerful GW emission is bound to the motion of large masses, and these typically have long periods/characteristic time scales. If we wish to go down, say, to the milli-Hertz frequency range then we need arm-lengths in the order of tens of millions of kilometres. This is far beyond what can be done on earth, not only because of the arm-length constraint but also because the so called gravity gradient noise\(^4\) at frequencies below \(\sim 1\) Hz are extremely difficult to reduce [7].

In the early 90s, and following earlier studies during the previous 15 years or so to build a GW detector in space, an idea began to take shape which has basically survived to this date. This

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\(^3\) Note the relationship \(\lambda_{GW} = \frac{c}{f_{GW}}\), which holds in the usual approximation that GWs are perturbations of flat space-time.

\(^4\) This is due to the motion of masses around the detector settlement, whether soil vibrations, mass displacements, air winds, etc.
is schematically shown in figure 1. The constellation of the three spacecraft will orbit the Sun at 1 AU, trailing the Earth by 20°, some 45 million km from us. The plane of the constellation is tilted by 60°, which ensures the best stability possible of the equilateral triangle formation across the year [8].

The intended sensitivity of LISA to GW signals is plotted in figure 3, along with that of LIGO for reference of the complementarity of these two instruments. The curves represent the (amplitude) spectral density of noise expressed in Hz$^{1/2}$, i.e., they represent the instrumental noise as if it was a GW noise blurring the interesting signals. These are indicated (for LISA) as “Resolved galactic binaries” and “Coalescence of Massive Black Holes”, which are very reliably

Figure 2. Left: LISA’s snapshot position in its heliocentric orbit. Note the tilt of the triangle plane relative to the ecliptic (60°) and the trailing angle behind the Earth (20°). Right: evolution of the constellation during one year. Note the normal to LISA’s plane describes a cone in the sky once a year, while the three satellites rotate clockwise around the barycentre of the triangle, also once per year.

Figure 3. Amplitude spectral noise of LISA (left curve) and LIGO (right curve). LISA seems to be noisier, but what matters is the signals each detector can actually sense. Note LISA is contaminated by what are called unresolved galactic binaries: LISA is signal-dominated at frequencies roughly below 1 mHz.
predicted signals visible to \textit{LISA}. In particular, a score or so of resolved galactic binaries will surely be detected by \textit{LISA}, as their GW signals can be calculated and are seen to fall within the detectability region. These binaries are the so called \textit{verification binaries} as they will provide a check of the performance of \textit{LISA} and a calibration procedure, too. Another important type of sources for \textit{LISA} is the capture and subsequent inspiral of a stellar compact object into a massive black hole at a galactic center, known as an extreme-mass-ratio inspiral (EMRI). Like every new instrument, though, we should be prepared for the unexpected, not just what we can at present predict on the basis of our current knowledge.

3. The \textit{LISA} instrument

To reach the sensitivity levels shown in figure 3 is a real scientific and technological challenge: we are talking about picometre interferometry over a baseline of 5 million km, and measurements are to be done at milli-Hz frequencies, which is also a non trivial problem in electronic circuitry. In this section we review the most relevant issues which arise while developing \textit{LISA}, as well as the solutions given to them.

First of all, for \textit{LISA} to make meaningful GW measurements, all six proof masses must (ideally) be in \textit{pure geodesic motion}, or \textit{free fall}, i.e., no non-gravitational forces should act on them which would deviate them from geodesic trajectories. In the case of \textit{LISA}, such trajectories are determined by the Sun, the planets, their moons, etc. plus the gravitational waves themselves. The latter however show up as \textit{gravity gradients} which result in relative accelerations between pairs of masses which have a specific signature, e.g., they vary with time with some characteristic patterns in a certain frequency band. The geodesic motion of \textit{LISA}’s proof masses, acting as interferometer mirrors, ensures that the GW induced phase shifts in the laser light is what is actually measured.

Such ideal situation is of course not feasible with real instruments: there are both \textit{external} potential disturbances (e.g., solar radiation pressure, cosmic and solar ionising particles, etc.) and internal ones (temperature fluctuations, magnetic fields, local gravitation, etc.) which tend to deviate the proof masses from pure free fall. A requirement is thus defined which sets a limit on the amount of \textit{noise} which can be tolerated for \textit{LISA} to meet its scientific objectives. This is what we see in figure 3, left; translated into relative acceleration between proof masses in distant spacecraft, the requirement is in the order of

$$S_{\Delta a}^{1/2}(\omega) \lesssim 3 \times 10^{-15} \text{ m s}^{-2} \text{ Hz}^{-1/2}$$

for \textit{LISA} (4)

leaving aside the frequency dependence which results in the V-shaped curve of figure 3. As we also see in the figure, \textit{LISA} is sensitive to likely GW signals between 0.1 mHz and 1 Hz provided the requirement above is met in the frequency band.

3.1. \textit{LISA}’s \textit{drag-free system}

Adverse conditions in the interplanetary medium must be avoided in the first place; the spacecraft hosting the proof masses provide this shielding, but this is not sufficient: the radiation pressure from the sunlight drags along the spacecraft with a tiny acceleration, so that the masses freely floating in their interiors would eventually crash against their walls, hence destroying the experiment.

To avoid this, a set of micro-thrusters is installed in the outer walls of each spacecraft which, upon detection of misplacement of the proof masses with respect to their centred position, are activated so that the spacecraft is gently driven back to the proof masses’ geodesic trajectories. The activation scheme is derived from the readouts of the so called Gravitational Reference Sensor (GRS), which determines the position of the proof masses by a set of capacitive sensors: each mass is floating in the interior of a box called \textit{electrode housing} whose interior walls have
Figure 4. Left: interior of the electrode housing. The proof mass is a 2 kg Au+Pt alloy cube forming capacitors with each of the electrodes in the walls. Right: an artist’s view of a LISA spacecraft from outside. Note two micro-thruster sets, dubbed FEEP in the drawing (for Field Effect Electric Propulsion, a thrust concept based on the emission and acceleration of ions from an on-board reservoir), which are suitably activated to counter the effect of proof mass misplacement relative to the housing, solidly linked to the satellite’s structure.

Electrodes making capacitors between them and the floating mass. A 100 kHz voltage is applied to these electrodes which enables a nanometre precision measurement of the gap size between the electrode and the proof mass. Figure 4 shows a real electrode housing and a drawing of micro-thrusters in a LISA spacecraft.

The combination of the GRS and the micro-thruster actuators is usually called the drag-free subsystem. This can also be partly driven by interferometer signals, one order of magnitude more sensitive than the capacitive sensors but only useful along the longitudinal degree of freedom in the direction of the remote spacecraft. This is an essential subsystem for LISA.

Figure 5. LISA interferometry: on the left and right we see (part of) the structure of two spacecraft, highlighting in particular the telescopes, used both to send and receive light to and from the other spacecraft. The diagram also shows the three step interferometry concept: the proof mass positions are first determined with respect to their host spacecraft (short range) then the distances between spacecraft are measured (long range), then all three measurements combined into a single one.
3.2. **LISA interferometry**

While the drag-free is necessary to make meaningful measurements, these measurements are effectively made by precision laser interferometry. In LISA the laser is infrared ($\lambda_{\text{laser}} = 1.064 \, \mu m$) and has a power of 2 watts. The light is sent to the remote spacecraft by means of a telescope (of the Cassegrain reflector type [9]), as it is collected on arrival, too —see figure 5. The distance between corresponding proof masses is determined in three steps: first the distance between a proof mass and its host satellite, which is a few centimetres, is measured with a local interferometer of the Mach-Zehnder type, identical to the one in *LISA PathFinder* [10] —see below. Next, the distance between remote spacecraft, in the order of 5 million kilometres is determined, and finally the distance between the remote spacecraft and, finally, the second proof mass position with respect to its host satellite is determined, like in the first step.

The *LISA PathFinder* interferometer has been extensively tested and is performing well above requirements, so it will be directly taken over into LISA. The most difficult part is therefore the second step, as the arm-length is not only extremely long, it is also varying with time. The reason is the LISA constellation is not totally stable, as we mentioned in section 2. The “instability” is not really an instability in the usual sense: in this context it refers to the fact that the relative positions between spacecraft varies during the year. This is reflected in three main effects: a) the distances between spacecraft vary (by about 60 000 km in one year, not very relevant as this happens at very low frequency —30 nano-Hz); b) the spacecraft move with respect to each other at velocities of 15 m/sec at most, which requires laser modulations in the range of 10 MHz to compensate for the associated Döppler shifts; and c) the angles between arms vary by about ±1.5°.

The latter, together with the finite time the laser light takes to travel along one LISA arm (16.7 seconds) complicate the practical implementation of the interferometry: first of all, the telescope structure must be able to slightly and quietly pivot to compensate for the angle variations, and second, a *point ahead mechanism* is in charge of pointing the laser beam to the position where the other satellite will be 16.7 seconds later. While local interferometry can be accurately designed and tested on ground, the long arm interferometry is of course impossible to implement directly in the laboratory, so it is studied combining optic and electronic devices [11, 12].

3.3. **Other LISA subsystems**

The subsystems described in the last two sections are definitely the most important ones from the conceptual point of view. However many more are needed in the real implementation of the satellites: thermal insulators to preserve a very demanding temperature stability (temperature fluctuations affect the proof mass mechanical stability, the optical elements’ properties, etc.), solar panels and batteries, on board computers to control the system workings, receive telecommands from ground and send telemetry, down-link antennas to make possible the communications, star-trackers to determine the satellite’s positions (using also detailed sky maps), diagnostics sensors and calibrators, etc. Figure 6 provides a few graphical hints.

4. **LISA PathFinder**

To meet the requirements of LISA is definitely not trivial. But, even beyond that, the very mission concept is very unusual in space science and engineering, as the spacecraft and the payload are actually deeply integrated: the spacecraft is much more than a mere vehicle, as it is heavily controlled by the payload itself and needs to respond with high precision.

The drag-free subsystem described in the previous section is extremely demanding —see equation (4)—, orders of magnitude more than any drag-free previously flown, and cannot possibly be tested in Earth. In particular because neither a parabolic flight nor a drop tower
can create a free fall environment for periods of time of several hours, as required by \textit{LISA}, which has to work in the sub-mHz frequency range.

These circumstances, together with the major challenge \textit{LISA} poses and its consequent high price, were the drivers to fly a technology precursor mission which would put to test in space the main subsystems of \textit{LISA}. A successful such mission would help reduce the risks of flying from scratch a fully new concept mission and, hopefully, create instrumentation which can be (almost) directly be carried over into \textit{LISA}.

This mission is \textit{LISA PathFinder} (LPF) and is led by the European Space Agency (ESA), with the contributions of seven countries (Germany, Italy, United Kingdom, Spain, Switzerland, France and the Netherlands) to its payload.

The LPF concept is to squeeze one of the three \textit{LISA} arms from 5 million kilometres to 30 cm (see figure 7, left), to fit it into a single spacecraft, and set up there a drag-free environment near the \textit{LISA} frequency band and with slightly less demanding requirements. More specifically,

\[ S_{\Delta a}^{1/2}(\omega) \lesssim 3 \times 10^{-14} \text{ m s}^{-2} \text{ Hz}^{-1/2} \quad \text{for LPF} \]  

in a frequency range between 1 mHz and 30 mHz. The margins in sensitivity and frequency band are intended to make LPF feasible while at the same time close enough to \textit{LISA}, so that the final step to the large mission is affordable on the basis of what we learn from LPF.

\section*{4.1. Quick overview of LPF instruments}

As already mentioned, one of the main subsystems in LPF is the \textit{drag-free}. This is implemented in LPF by means of two cylindrical vacuum enclosures (VE), where the electrode housings (see figure 4, left panel), containing the proof masses, are hosted. This VE preserve pressure conditions at $10^{-5}$ Pascal, and this is done with so called getter pumps, which is a material that captures the particles which constantly escape from the various surfaces altogether (\textit{outgassing}). The mass positioning signals are processed by the On-Board Computer (OBC) which activates the micro-thrusters as required.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure6.png}
\caption{On \textit{LISA} spacecraft interior. The drawing is not comprehensive, and just gives a qualitative flavour of the parts there.}
\end{figure}
Figure 7. Left: schematics of the LPF concept: the two proof masses are enclosed in a single spacecraft, at 30 cm from each other and whose distance is measured by a Mach-Zehnder laser interferometer. Right: Lagrange points of the Sun-Earth system. LPF will orbit around L1 as shown in the diagram.

The space in between is occupied by the Optical Bench (OB), which contains various optical elements (mirrors, beam-splitters, photo-diodes and fibre injectors) to do the interferometry. The interferometer is a heterodyne Mach-Zehnder [13]; actually, up to four such interferometers are implemented in parallel in the LPF OB, each to measure a relevant signal: the main one is the differential channel, i.e., the distance between the two proof masses, the other three being the distance of one of the proof masses to the spacecraft structure and two more, one for frequency reference and the other for laser frequency stabilisation.

Another very important subsystem is the Diagnostics Subsystem which includes thermal,
Figure 9. Left: Performance of the LPF thermal sensors and their electronics. The dashed lines indicate the LPF requirements, i.e., they are below and to the right of these lines. As can be seen, the spectral density is below $10^{-5} \, \text{K Hz}^{-1/2}$ down to $10^{-4} \, \text{Hz}$, a remarkable achievement. Right: sensitivity of various magnetic sensors. The *fluxgate* (black dashed line) is the one which will fly in LPF, while the rest are AMR (Anisotropic Magneto-Resistance) in various configurations. Again, dash-dotted lines define the LPF requirements and we see that all magnetometers are compliant with it, but they are even good down to $10^{-4} \, \text{Hz}$.

magnetic and charged particle detectors, along with calibration devices. This subsystem has been fully developed at *IEEC*, Barcelona. Apart from monitoring to high precision various disturbances in the LTP, the diagnostics subsystem provides a way to identify the real effect of those disturbances on the interferometer readout, i.e., to determine which part of the total system noise is of thermal or magnetic origin. Given the enormous stability required in the LTP, the diagnostics items have to be extremely sensitive, too. In Figure 9 we see the performance of the thermal sensors (NTC thermistors) and magnetic sensors. Deliberately, the plots stretch down to $10^{-4} \, \text{Hz}$, one order of magnitude below the LPF requirement, but in the lower part of the *LISA* band. The results show that *LISA* is already within reach if the requirements on these diagnostics items do not differ significantly from those of LPF [14]. This is still an open question, but the plots definitely indicate we are on track. In addition, the development of tinier and yet sensitive magnetometers is a real must for *LISA*, as the current fluxgates have very serious setbacks: they have poor space resolution (because of their size), they must be kept far from the proof masses (due to magnetic back-action), and only a few can be installed (due to size and price). In this respect the research we are carrying forward at *IEEC* is very valuable for *LISA*, and the results so far look really encouraging [15].

The *LPF* Radiation Monitor (RM) is designed to obtain short term information on charged particles hitting the spacecraft and possibly reaching the proof masses, thereby distorting the measurements of the GRS. Due to the protection provided by the spacecraft and the VE, only particles with a primary energy above 70 MeV can go through[16], hence the RM has its particle detectors (PIN diodes) hidden in a copper shield of cubic shape with bevelled corners and a thickness of 6.4 mm —figure 10. By counting particles with those energies, it becomes possible and meaningful to study correlations between the RM readings and the charge management system of the LTP [17].

The DMU is the LTP computer. It controls all the diagnostics items and their interfaces, plus processes and sends information with various other subsystems, e.g., the phase-meter of the interferometer channels, caging mechanism, etc. In hardware it embodies three pairs of Printed Circuit Boards (PCB) —see figure 10—, duplication being implemented as redundancy for security requirements. The DMU requires software to execute its functionality, and this is
organised in two blocks: the Boot Software (BSW) and the Application Software (ASW). The former is a sort of mini-operating system (61 kbytes) which starts-up the system and takes care of several tasks, such as upgrading of the ASW in flight. The ASW receives telecommands from ground to drive the LTP experiment according to the general mission plan [18], and to send data and telemetry to the OBC, the main mission computer. The DMU software has been extensively tested, with consistently excellent results.

5. Conclusions

*LISA* is a complex and expensive mission, but it has a strong scientific case, as it will bring about a new way to observe the Universe. A way which may give us access to the unknown 96% of the Universe which does not shine in the electromagnetic channels of telescope Astronomy, but which does gravitate, hence perhaps generates GWs with an immense potential for discovery. In this brief review we have highlighted some of the features of *LISA* as currently conceived. At the time of writing (April–2011), however, new events are taking place which may change some of the statements made above regarding specific aspects of *LISA*’s performance; these have not been reflected in the text because they are still not consolidated. Nevertheless the main facts about *LISA* will definitely not affect either its scientific interest or its relevance.

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**References**

[1] Albert Einstein *et al.* 1952 *The Principle of Relativity* (New York: Dover)
[2] Einstein A 1918 *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften zu Berlin* 154
[3] Weisberg J and Taylor J 2010 Timing Measurements of the Relativistic Binary Pulsar PSR B1913+16 *(Preprint http://arxiv.org/abs/1011.0718)*
[4] Duncan R Lorimer 2008 Binary and Millisecond Pulsars, Living Reviews in Relativity, available on-line at http://relativity.livingreviews.org/Articles/lrr-2008-8

[5] Lobo A 1992 Classical and Quantum Gravity 9 1385

[6] Stefan Hild 2009 How to listen to the Universe? Optimising future GW observatories for astrophysical sources, available on-line at http://ww.sr.bham.ac.uk/~hild/presentations/nikhef_hild.pdf

[7] Creighton T 2008 Classical and Quantum Gravity 25 125011

[8] WM Folkner, F Hechler, TH Sweetser, MA Vincent, PL Bender 1997 Classical and Quantum Gravity 14 1405

[9] Cassegrain reflector, see e.g. Wikipedia at http://en.wikipedia.org/wiki/Cassegrain_reflector

[10] G Heinzel et al 2004 Classical and Quantum Gravity 21 581

[11] JI Thorpe RJ Cruz S S and Mueller G 2005 Classical and Quantum Gravity 22 227

[12] H Halloin, O Jeannin, B Argence, V Bourrier, E de Vismes, P Prat 2010 LISA On Table: an Optical Simulator for LISA, Proceedings of the 2010 International Conference on Space Optics, Rhodes (Greece), available on-line at http://congrex.nl/icso/Papers/Session%2014b/FCXNL-10A02-2018762-1-Halloin_ICSO_Paper.pdf

[13] G Heinzel et al 2003 Classical and Quantum Gravity 20 S153

[14] J Sanjuán, J Ramos-Castro, A Lobo 2009 Classical and Quantum Gravity 26 094009

[15] I Mateos, A Lobo, J Ramos-Castro, J Sanjuán, M Nofrarias 2009 Journal of Physics: Conference Series 154 012005, available on-line at http://iopscience.iop.org/1742-6596/154/1/012005

[16] Araújo HM et al 2005 Astroparticle Physics 22 451

[17] D Shaul, T Sumner and A Lobo 2008 Analysis of Data from the Radiation Monitor on LISA PathFinder Tech. rep. ICL and IEEC, S2-ICL-TN-3019

[18] L Gesa and A Conchillo 2010 ASW Requirements Tech. rep. IEEC and NTE, S2-NTE-SRD-3003