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MISSIONS SPATIALES EN PHYSIQUE FONDAMENTALE

SPACE MISSIONS FOR FUNDAMENTAL PHYSICS

DOSSIER

Gravitational wave detection by laser interferometry – on earth and in space

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Abstract. The space project LISA is approved by ESA as a cornerstone mission in the field of 'fundamental physics', sharing its goal and principle of operation with the ground-based interferometers currently under construction: the detection and measurement of gravitational waves by laser interferometry. Ground and space detection differ in their frequency ranges, and thus the detectable sources. At low frequencies, ground-based detection is limited by seismic noise, and yet more fundamentally by 'gravity gradient noise', thus covering the range from a few Hz to a few kHz. On five sites worldwide, detectors of armlengths from 0.3 to 4 km are being built, two of them in Europe (GEO and VIRGO). They will progressively be put in operation between 2001 and 2003. Future improved versions are being planned, with data not until 2008, i.e. near the launch of the space project LISA. It is only in space that detection of signals below, say, 1 Hz is possible, opening a wide window to a different class of interesting sources of gravitational waves. The project LISA consists of three spacecraft in heliocentric orbits, forming a triangle of 5 million km sides. © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

gravitational wave / LISA mission / space interferometer / gravitational sensor

Détection des ondes gravitationelles par interférométrie laser – sur Terre et dans l'espace

Résumé. *Le projet spatial* LISA *a été approuvé par l'*ESA, *en tant que « pierre angulaire » dans le domaine de la physique fondamentale. Ses objectifs et son principe sont les mêmes que ceux des interféromètres terrestres actuellement en construction : détecter et observer le rayonnement gravitationnel par interférométrie laser. Les interféromètres spatiaux et terrestres diffèrent essentiellement par le domaine de fréquence dans lequel ils seront sensibles, et donc par les types de sources qu'ils observeront. Les détecteurs terrestres sont limités en basses fréquences par le bruit sismique et les gradients de gravitation : ils seront sensibles entre quelques* Hz *et quelques* kHz. *Cinq détecteurs sont actuellement en construction dans le monde, dont deux en Europe (*GEO *et* VIRGO*). Ils entreront progressivement en fonctionnement, entre* 2001 *et* 2003. *La recherche vers des instruments*

Note présentée par Pierre ENCRENAZ.

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de seconde génération, qui pourraient commencer à fonctionner vers 2008*, en même temps que* LISA*, est déjà commencée. Seul l'espace permet d'espérer la détection entre* 10^{-4} Hz *et* 0.1 Hz*, domaine couvert par* LISA*, qui sera constitué de trois satellites en orbites héliocentriques, formant un triangle équilatéral de* 5 *millions de km de côté. Les sources détectables par* LISA *seront plus massives et plus intenses que celles détectables par les interféromètres terrestres.*

ondes gravitationnelles / mission spatiale LISA / interféromètre spatial / capteur gravitationnel

1. Introduction

In this ONERA conference devoted to 'Fundamental Physics in Space' we will also have a contribution on interferometric gravitational wave detectors located firmly on the Earth's surface. We will briefly discuss most of the larger GW detectors being built right now. In this talk we will learn how the detectors on ground and in space differ, where aims and technologies overlap, and what can scientifically be gained from the complementarity of these researches. Some special attention will be given to the efforts in Europe.

2. Gravitational waves

Gravitational waves of measurable strengths are emitted only when large cosmic masses undergo strong accelerations, for instance — as shown schematically in *figure 1* — in the orbits of a (close) binary star. The effect of such a gravitational wave is an apparent strain in space, transverse to the direction of propagation, that makes distances ℓ between test bodies shrink and expand by small amounts $\delta\ell$, at twice the orbital frequency. The strength of the gravitational wave, its 'amplitude', is generally expressed by $h = 2\delta\ell/\ell$. An interferometer of the Michelson type, typically consisting of two orthogonal arms, is an ideal instrument to register such differential strains in space.

'So where's the problem?' one might ask. It lies in the magnitude, or rather: the smallness, of the effect.

2.1. Strength of gravitational waves

From a supernova, or the in-spiral of a close neutron star binary out at the Virgo cluster (a cluster of 2000 galaxies, 10 Mpc away), we could expect a strain of something like $h \approx 10^{-22}$. So all we have to do

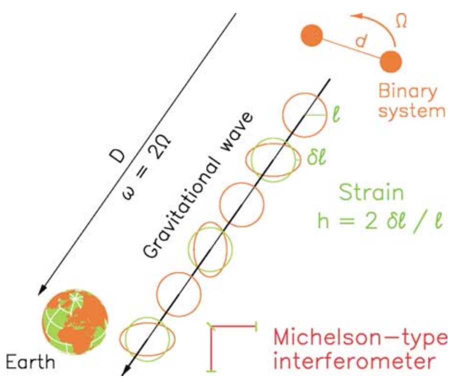

Figure 1. Generation and propagation of a gravitational wave emitted by a binary system.

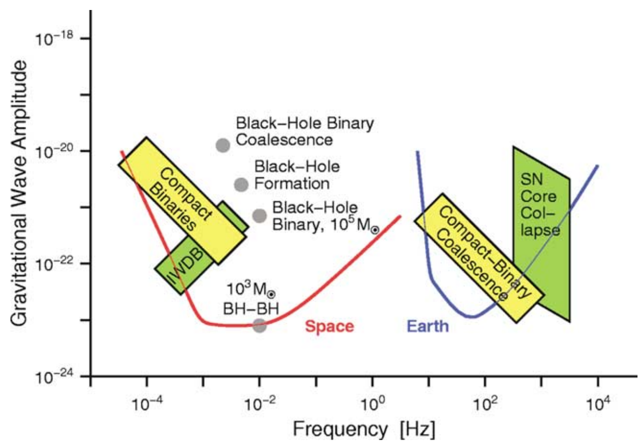

Figure 2. Some sources of gravitational waves, with sensitivities of Earth and space detectors.

is to measure — in a Michelson interferometer of kilometer dimensions — path changes in the order of 10^{-19} m. Hopeless? The prototypes of ground-based interferometers bear evidence that it is within reach.

And yet, despite the smallness of the interaction, gravitational waves are by no means a 'weak' phenomenon. On the contrary, they are linked with cosmic events of high energy transfers. Two examples show this clearly. The binary system containing the Hulse–Taylor pulsar PSR 1913+16, much publicised through the 1993 Nobel prize, loses its orbital energy primarily through the emission of gravitational radiation; no other loss mechanism comes anywhere near it. A *supernova*, on the other hand, during its millisecond collapse, emits more power than the luminescence of all the stars of the universe combined. Most of this is in neutrinos, but an appreciable part also is in gravitational waves.

2.2. Complementarity of ground and space observation

Figure 2 shows some typical sources of gravitational radiation. They range in frequency over a vast spectrum, from the kHz region of supernovae and final mergers of compact binary stars down to mHz events due to formation and coalescence of supermassive black holes. Indicated are sources in two clearly separated regimes: events in the range from, say, 5 Hz to several kHz (and only these will be detectable with terrestrial antennas), and a low-frequency regime, 10^{-5} to 1 Hz, accessible only with a space project such as LISA. In the following sections we will see how the sensitivity profiles of the detectors come about. No detector covering the whole spectrum shown could be devised.

Clearly, one would not want to miss the information of either of these two (rather disjoint) frequency regions. The upper band, with supernovae and compact binary coalescence can give us information about relativistic effects and equations of state of highly condensed matter, in highly relativistic enviromnments. Binary inspiral is an event type than can be calculated to high post-Newtonian order, as shown by Blanchet [1]. This will allow tracing the signal, possibly even by a single detector, until the final merger, a much less predictable phase. The ensuing phase of a ring-down of the combined core does again lend itself to an approximate calculation. Chances for detection are reasonably good, but not by wide margins.

The events to be detected by LISA, on the other hand, may have extremely high signal-to noise ratios, and failure to find them would shatter the very foundations of our present understanding of the universe. The strongest signals will come from events involving (super-)massive black holes, their formation as well when galaxies with their BH cores collide. But also the (quasi-continuous) signals from neutron-star and black-hole binaries are among the events to be detected ('Compact Binaries' in *figure 2*). Interacting white dwarf binaries inside our galaxy ('IWDB' in *figure 2*) may turn out to be so numerous that they cannot all be resolved as individual events. Catastrophic events such as the gamma-ray bursts are not yet well enough understood to estimate their emission of gravitational waves, but there is a potential of great usefulness of GW detectors mainly at low frequencies. The combined observation with electromagnetic and gravitational waves could lead to a deeper understanding of the violent cosmic events in the far reaches of the universe.

3. Ground-based interferometers

The underlying concept of all our detectors is the Michelson interferometer (see schematic in *figure 3*), in which an incoming laser beam is divided into two beams travelling along different (perpendicular) arms. On their return, these two beams are recombined, and their interference (measured with a photodiode PD) will depend on the difference in gravitational wave effects that the two beams have experienced.

The changes δL in optical path become the larger the longer the optical paths L are made, optimally about half the wavelength of the gravitational wave: e.g. to a seemingly unrealistic 150 km for a 1 kHz signal. Schemes were devised to make the optical path L significantly longer than the geometrical arm length ℓ, which is limited on Earth to only a few km. One way is to use 'optical delay lines' in the arms, the beam being folded back and forth between two concave mirrors (a modest version of this is shown in *figure 4*). The other scheme is to use Fabry–Perot cavities (*figure 3*), again with the aim of increasing the interaction time of the light beam with the gravitational wave.

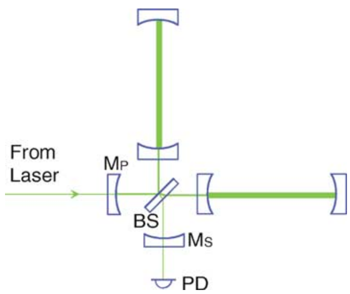

Figure 3. Advanced Michelson interferometer: mirrors $\mathrm{M_P}$, $\mathrm{M_S}$ for power and signal recycling.

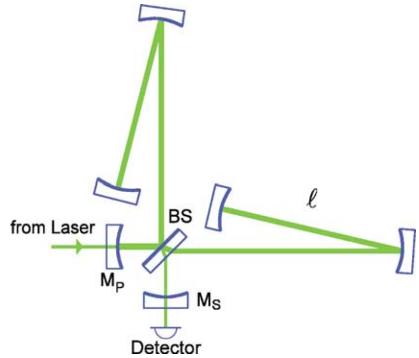

Figure 4. The DL4 configuration with dual recycling to be used in GEO 600.

For GW frequencies beyond the inverse of the storage time, the response of the interferometer will, however, roll off with frequency, with Fabry–Perots in the arms as $1/f$.

3.1. The detector prototypes

After pioneering work by Rai Weiss at MIT (1972), other groups at Munich/Garching, at Glasgow, then Caltech, Paris/Orsay, Pisa, and later in Japan and Australia, also entered the scene. Their prototypes range from a few meters up to 30, 40, and even 100 m. An alternative detection scheme, a Sagnac configuration, is being investigated at Stanford.

It is a fortunate feature that on our way to the full-fledged detectors we were able to go through generations of ever-improving prototypes. Even though some of these prototypes have reached the sensitivities of cryogenic resonant-mass antennas, they were never meant to be used as detectors, but rather as test-beds to verify new schemes and configurations devised to overcome otherwise limiting noise effects.

The 'phase noise' reduction achieved in these prototypes approaches that required in terrestrial interferometers, and is by many orders of magnitude better than required (at low frequencies) for a space mission.

3.2. The large-scale projects

Table 1 gives an impression of the wide international scope of the interferometer efforts, listed roughly according to size of detector.

All of the large-scale projects will use low-noise Nd:YAG lasers ($\lambda = 1.064$ µm), pumped with laser diodes for high overall efficiency. A wealth of experience has accumulated on highly stable and efficient lasers, and the space mission will profit from that.

The largest is the US project named LIGO [2]. It comprises two facilities at two widely separated sites. Both will house a 4 km interferometer, Hanford an additional 2 km one. At both sites construction has long been completed, installation of the optics in the vacuum enclosures is in progress, and first locking of the 2 km interferometer has been achieved. These three interferometers are designed for coincidence operation, and thus could be used for autonomous measurements.

Next in size (3 km) is the French–Italian project VIRGO [3], being built near Pisa, Italy. An elaborate seismic isolation system, including seven-stage pendulums, will allow measurement down to GW frequencies of 10 Hz or even below, but still no overlap with the space interferometer LISA (more details below).

For the detector of the British–German collaboration, GEO 600 [4], with a de-scoped length of 600 m, construction and installation of most of the optics in the vacuum system are finished, first power recycling

Table 1. Current and future projects of ground-based GW detectors.

Country	USA		FRA	ITA	GER	GBR	JPN
Institute	MIT,	Caltech	CNRS	INFN	MPQ	Glasgow	NAO, U-Tokyo, ICRR
Large interferomagnetic detectors: the current generation							
Project name:	LIGO		VIRGO		GEO 600		TAMA 300
Arm length ℓ	4 km 2 km	4 km	3 km		600 m		300 m
Site	Hanford	Livingston	Pisa		Hannover		Mitaka
(State)	(WA)	(LA)	ITA		GER		JPN
Large inferomagnetic detectors: the bright future							
Planning (start)	1995		1999				1998
Arm length ℓ	4 km	4 km	3 km				3 km
Site	Hanford	Livingston					Kamioka
(State)	(WA)	(LA)	Europe				Japan
Project name	Advanced LIGO		EURO				LCGT
Special features	active isolation suspension, RSE		high seismic rejection; cryogenic, diffractive optics, tunable				cryogenic underground

tests with a single arm were successful. The beam splitter is to be installed in May 2001. GEO 600 will employ advanced optical techniques such as 'signal recycling' to make up for the shorter arms.

In Japan, on a site at the National Astronomical Observatory in Tokyo, construction, vacuum system, and optics installation of the detector called TAMA 300 ([5] and many detailed papers in the same volume) with 300 m armlength are completed, and several data runs of the Michelson have been successful, but as yet without power recycling. It is, just as LIGO and VIRGO, equipped with standard Fabry–Perot cavities in the arms.

Australia also had to cut back from earlier plans of a 3 km detector. Currently a 80 m prototype detector, modeled somewhat after GEO 600, is being built to investigate new interferometry configurations. The design and the site will allow later extension.

As it happens, these projects are scheduled such that first operation can be expected around the years 2001/02. It is fortunate that the various projects are rather well in synchronism. For the received signal to be meaningful, coincident recordings of at least two detectors at well-separated sites are essential. A minimum of three detectors is required to locate the position of the source, and there is general agreement that only with at least four detectors can we speak of a veritable gravitational wave astronomy.

4. Noise and sensitivity

The measurement of gravitational wave signals is a constant struggle against the many types of noise entering the detectors. Three such noise sources, the most prominent ones, will be discussed below.

4.1. Seismic noise

The mirrors between which the distances are to be monitored are suspended as pendulums in vacuum, to isolate them from extraneous vibrations: from seismic and acoustic noise. Various schemes (pendulum suspension, lead-and-rubber stacks, even active position control) are used (often in combination) to reduce seismic noise by many powers of 10, which is relatively easy for frequencies above, say, 100 Hz. It is only

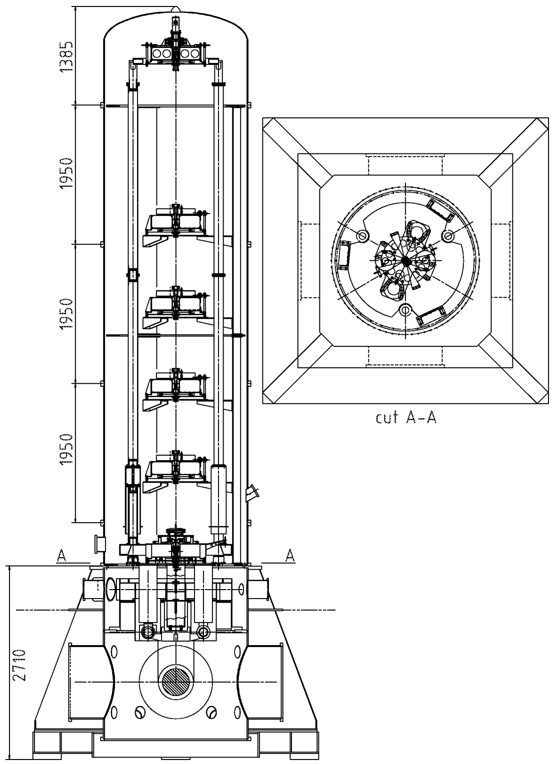

Figure 5. Super-attenuator suspension in VIRGO.

with extreme effort that this lower frequency bound can be lowered to 10 Hz or less. Not only does the natural noise rise towards low frequencies, but also the pendulum isolation becomes less efficient. This causes the very steep rise to low frequencies in the plot of *figure 2*. VIRGO has developed an extremely powerful seimic isolation system, the 'super-attenuator', consisting of a series of 6 successive pendulum stages, in conjunction with an 'inverted pendulum', and an active isolation stage. This suspension will allow VIRGO to extend GW search to lower frequencies than other terrestrial detectors. *Figure 5* shows such an attenuator in side and plan view [3]. The total height is about 10 m. Preloaded cantilever springs in each stage provide excellent vertical isolation.

4.2. Thermal noise

All optical components — and in particular the mirrors — will cause fluctuations in the optical paths due to their thermal vibrations, their Brownian motion. The noise coming from the pendulum mode is most prominent at low frequencies, rolling off steeply towards higher frequencies. The noise due to substrate modes rolls off less steeply and is thus a serious disturbance at intermediate frequencies.

By choice of materials (high mechanical Q) and appropriate shaping of the substrates (to keep their resonant frequencies above our kHz range) the effect of these thermal motions can be reduced.

Intensive research is going on into the development and choice of appropriate materials for the mirror substrates (pure fused silica, sapphire), and the proper treatment for attaining the highest mechanical Q, e.g. several 10^7. Such high values can be maintained only if the bonding to the suspension 'wires' does not introduce losses. Bonding techniques, using material identical to the substrate (monolithic suspension), special fibers, or thin ribbons are required. Efficient collaboration between the European groups has given very promising results.

But for both of the thermal noise effects, the internal vibrations of the mirrors as well as the pendulation mode, and similarly also for the seismic disturbances, the sensitivity goal can only be reached if we choose the armlength ℓ long enough. This is where our need for kilometer dimensions comes from. The left-hand side of the sensitivity curve 'Earth' in *figure 2* is mainly due to the seismic and vibrational noise.

4.3. Shot noise

Particularly at higher frequencies, the sensitivity is limited by another fundamental source of noise, the so-called shot noise, a fluctuation in the measured interference coming from the 'graininess' of the light. These statistical fluctuations 'fake' apparent fluctuations in the optical path difference ΔL that are inversely proportional to the square root of the light power P used in the interferometer. For the very ambitious aims of the 'advanced' detectors, about 10 kW of light power, in the visible or the near infrared, would be required. This is not as unrealistic as it may sound; it can be realized by the concept of 'power recycling'.

The laser interferometers are planned to monitor the (gravitational-wave induced) changes δL of the light path by observing the dark fringe of the interferometer in one output port. The (unused) light going out at the other port of the beam splitter can be fed back, via a mirror $\mathrm{M_P}$, and in correct phase with the incoming light (*figures 3, 4*), so that the circulating light power is significantly enhanced. This scheme was proposed by Ron Drever in 1981, at the same time as Roland Schilling saw it come as a natural consequence in the Garching 30 m prototype, where the appropriate feedback had already been implemented for an efficient frequency stabilisation of the laser.

Shot noise is a 'white' noise, but due to the response rolling off with $1/f$ at higher frequencies, the apparent noise rises with frequency, in the manner shown in the curves 'Space' and 'Earth' in *figure 2*.

4.4. Advanced interferometry configurations

An additional 'recycling' scheme was later proposed by Brian Meers, and forms the baseline for the GEO 600 interferometer: 'signal recycling'. A further mirror, $\mathrm{M_S}$, is added to the interferometer, this one in the output port. The microscopic position of this mirror can be adjusted such that the signal sideband is also resonant in the interferometer, providing an enhancement of the signal, with possibly reduced measuring bandwidth. Schemes like this 'dual recycling', or the related 'Resonant Sideband Extraction (RSE)', are expected to be employed in future upgrades also of the other detectors.

The curve marked 'Earth' in *figure 2* indicates the sensitivities that will eventually be reached with the planned large interferometers, at least in their future advanced versions.

5. Next-generation ground-based detectors

In the mean time, it is essential to develop a next generation of detectors. The study of new technologies to be employed, of new materials, of advanced interferometric configurations has to be pushed forward, so that the necessary new implementations can be undertaken in or around the year 2005.

Three plans for such next-generation detectors have been put forward, which are entered in the lower part of *table 1*: Advanced LIGO, LCGT, and EURO.

5.1. Status of the three future projects

Advanced LIGO Among these, the proposed US project is furthest progressed, and literature on the concept exists. Advanced LIGO has made full usage of the common efforts in the LIGO Scientific Collaboration (LSC). For locations, Advanced LIGO will rely on the existing sites at Hanford and Livingston. The advantage is clear: no cost for new sites, for civil and vacuum engineering. One drawback is that the incorporation of more 'aggressive' approaches (cryogenics, all-refractive optics, Sagnac) is not so easy to realize, and that the option of lower seismic noise of underground sites is forfeited.

The Advanced LIGO groups of LSC have come up with simulations of the expected sensitivity that indicate that an operation limited only by the optics noise (shot noise, radiation pressure noise) appears possible. The suspension would have to be modeled after the GEO 600 triple pendulum concept, mirrors being made from large substrates of sapphire (or YAG), the schemes of signal recycling or RSE have to be used.

LCGT The concept of the Japanese project 'Large Cryogenic Gravitational wave Telescope' (LCGT) is also rather well defined; it will use super-cooled (cryogenic) mirrors. The location of LCGT will be deep inside the mountain that houses the famous neutrino detector Super-Kamiokande. The ground noise is by nearly two orders of magnitude lower than at ground level. The armlength will be 3 km, and an existing tunnel can be used for one arm.

EURO Even more ambitious is the concept of the European detector EURO. The four funding agencies (CNRS, MPG, INFN, PPARC) of France, Germany, Italy, and the UK, agreed to pursue the definition of a common European high-sensitivity detector. However, the completion and commissioning of the current projects, GEO 600 and VIRGO, has the highest priority. Thus, the actual beginning of the project may be as late as 2008. A site deep underground (as for LCGT) is preferred, but not yet decided upon.

5.2. The European project EURO

Conceived is a detector that will, within a given frequency range, be limited only by quantum effects. This frequency range is to be chosen so that the most promising, and/or the most scientifically rewarding sources can be detected (and measured).

Simulations were carried out, using parameter sets from optimistic, but not unreasonable assumptions: 1 kW laser power; 1 tonne test masses; moderate cryogenics (30 K); gravity gradient negligible above 10 Hz; arm-length 3 km; underground site (significantly reduced seismic noise); extreme seismic rejection down to low frequencies, for which the VIRGO super-attenuator might be a viable approach.

An operation limited only by the (quantum-)optical noise, i.e. solely by shot noise and radiation pressure noise, seems possible, using classical techniques, but going to the ultimate frontier of current technologies.

6. Space interferometer LISA

Only a space mission allows us to investgate the gravitational wave spectrum at very low frequencies. For all ground-based measurements, there is a natural, insurmountable boundary towards lower frequencies. This is given by the (unshieldable) effects due to varying gravity gradients of terrestrial origin, meteorological phenomena as well as motions inside the Earth. To overcome this 'brick wall', the only choice is to go far enough away, either into a wide orbit around the Earth, or better yet further out into interplanetary space. The European Space Agency (ESA) and NASA have recently agreed to collaborate on such a space mission called LISA, 'Laser Interferometer Space Antenna' [6].

Once we have left our planet behind and find ourselves in outer space, we have some great benefits for free: to get rid of terrestrial seismic and gravity gradient noise, to have excellent vacuum along the arms, and in particular to be able to choose the arm length large enough to match the astrophysical sources we want to observe.

LISA consists of three identical spacecraft, placed at the corners of an equilateral triangle (*figure 6*). The sides are to be 5 million km long ($5 \cdot 10^9$ m). This triangular constellation is to revolve around the Sun in an Earth-like orbit, about 20° (i.e. roughly 50 million km) behind the Earth. The plane of this equilateral triangle needs to have an inclination of 60° with respect to the ecliptic to make the common rotation of the triangle most uniform. The small orbit correction manoeuvres required can be made with field-effect Cs-ion propulsion units. These spacecraft form a total of three, but not independent, Michelson-type interferometers, here of course with 60° between the arms.

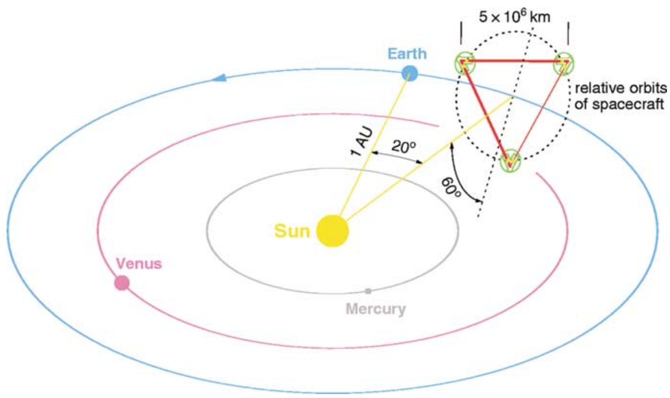

Figure 6. Orbits of the three spacecraft of LISA.

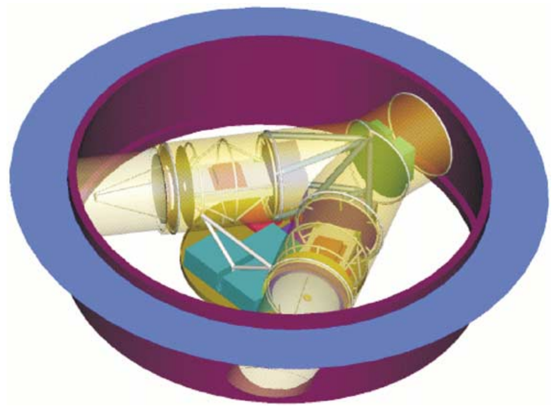

Figure 7. View of one LISA spacecraft.

The spacecraft at each corner will have two optical assemblies that are pointed, subtending an angle of 60°, to the two other spacecraft (indicated in *figure 7*, with the Y-shaped thermal shields shown semi-transparent). An optical bench, with the test-mass housing in its center, can be seen in the middle of each of the two arms, and telescopes of 30 cm diameter at the outer ends. Each of the spacecraft has two separate lasers that are phase-locked so as to represent the 'beam-splitter' of a Michelson.

6.1. Gravitational sensors

The distances are measured from test masses housed 'drag-free' in the three spacecraft.

The three LISA spacecraft each contain two test masses, one for each arm forming the link to another LISA spacecraft. The test masses of the gravitational sensors reflect the light coming from the YAG laser and define the reference mirror of the interferometer arm. These test masses are to be freely floating in space.

For this purpose these test masses are also used as inertial references for the drag-free control of the spacecraft that constitutes a shield to external forces. Development of these sensors is being done at various institutions. *Figure 8* shows the sensor modeled after already space-proven developments at ONERA [7].

These sensors feature a three axis electrostatic suspension of the test mass with capacitive position and attitude sensing. A resolution of 10^{-9} m/$\sqrt{\text{Hz}}$ is needed to limit the disturbances induced by relative motions of the spacecraft with respect to the test mass, for instance, the disturbances due to the spacecraft self gravity or to the test-mass charge.

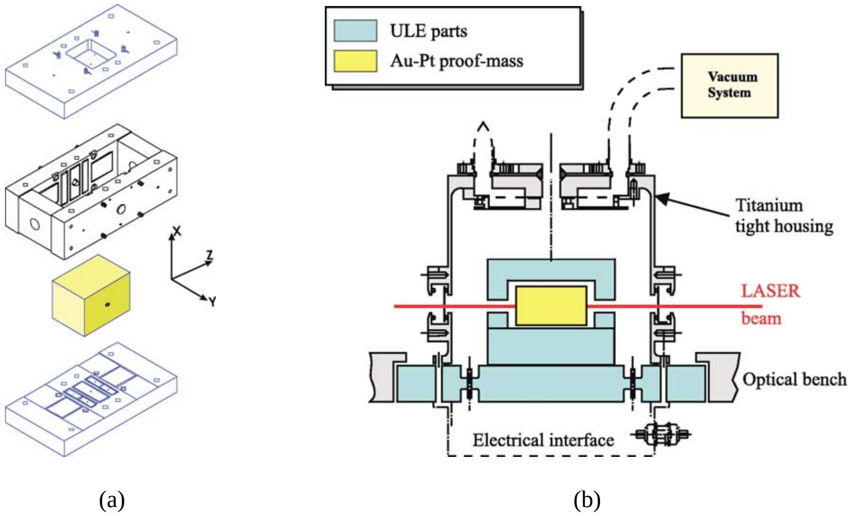

Figure 8. CAESAR overview: (a) the sensor cage; (b) sensor configuration.

6.2. Noise in LISA

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

Because of the low level of light power received, shot noise plays a major role in the total noise budget of spurious displacements. With a myriad of other, smaller, noise contributions the total apparent noise amounts to something like $\widetilde{\delta L} \approx 20 \cdot 10^{-12}$ m$/\sqrt{\text{Hz}}$. For signals monitored over a considerable fraction of a year, the sensitivity is about $h \approx 3 \cdot 10^{-24}$. The expected sensitivity (as function of frequency) is indicated in *figure 2* by the curve marked 'Space'.

Some of the gravitational wave sources are guaranteed to be much larger. Failure to observe them would cast severe doubts on our present understanding of the laws that govern the universe. Successful observation, on the other hand, would give new insight into the origin and development of galaxies, existence and nature of dark matter, and other issues of fundamental physics.

LISA is approved by ESA as a cornerstone mission under Horizons 2000. A System and Technology Study [6] has substantiated that improved technology, lightweighting, and collaboration with NASA can lead to a considerable reduction of cost. Thus, a new, faster, cheaper, and better approach, together with NASA, is being pursued, with launch foreseen around the year 2010.

This would approximately coincide with the first operation of the next-generation ground based detectors.

7. Conclusion

The difficulties (and thus the great challenge) of gravitational wave detection stem from the fact that gravitational waves have so little interaction with matter, and thus also with the measuring apparatus. Great scientific and technological efforts, large detectors, and a good deal of patience are required to detect and to measure this elusive type of radiation.

And yet — just on account of their weak interaction — gravitational waves (just as neutrinos) can give us knowledge about cosmic events to which the electromagnetic window will be closed forever. This goes for the processes in the (millisecond) moments of a supernova collapse, as well as of the many mergers of binaries that might be hidden by galactic dust. And it is also true for the distant, but violent, mergers of galaxies and their central (super)massive black holes.

In this way, gravitational wave detection can be regarded as a new window to the universe, but to open this window we must continue on our way in building and perfecting our antennas. It will only be after these large interferometers are completed (and perhaps even only after the next generation of detectors) that we can reap the fruits of this enormous effort: a sensitivity that will allow us to look far beyond our own galaxy, perhaps to the very limits of the universe.

References

[1] Blanchet L., C. R. Acad. Sci. Paris Sér. IV 2 (2001) 1343.
[2] Abramovici A., Althouse W.E., Drever R.W.P, Gürsel Y., Kawamura S., Raab F.J., Shoemaker D., Sievers L., Spero R.E., Thorne K.S., Vogt R.E., Weiss R., Whitcomb S., Zucker M.E., LIGO: The Laser Interferometer Gravitational-Wave Observatory, Science 256 (1992) 325–333.
[3] Vicere A., The VIRGO experiment, in: AIP-Conference-Proceedings, Vol. 555, AIP, 2001, pp. 138–145.
[4] Rüdiger A., Danzmann K., The GEO 600 gravitational wave detector, in: Gyros, Clocks, Interferometers: Testing Relativistic Gravity in Space, Springer Lecture Notes in Physics, Vol. 562, Springer, 2001, pp. 131–140.
[5] Fujimoto M.K., Overview of the TAMA project, in: Gravitational Wave Detection II, Universal Academy Press, Tokyo, 2000, pp. 41–43.
[6] LISA: System and Technology Study Report, ESA document ESA-SCI 11, July 2000.
[7] Touboul P. et al., C. R. Acad. Sci. Paris Sér. IV 2 (2001) 1271.