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GEO 600

A 600 m Laser Interferometric Gravitational Wave Antenna

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Abstract

This report is largely based on a proposal for a gravitational wave detector with 600 m arms, to be built in Hannover by a collaboration involving the University of Hannover, the Max-Planck-Institut für Quantenoptik (MPQ) at Garching, the University of Glasgow and the University of Wales, College of Cardiff [1].

The detector will incorporate a four-pass optical delay line, and power recycling and signal recycling will be used. Illumination will be provided at 1.06 μm by a Nd:YAG laser operating at a power of up to 10 W. The test masses will be suspended as double pendulums using fused silica fibres, and isolation will be provided by antivibration stacks.

The civil engineering work will be undertaken under the direction of Hannover, the vacuum system will be constructed by Hannover with assistance from Rutherford Appleton Laboratory, the technology will be developed by Hannover, MPQ and Glasgow working in close collaboration; theoretical input on astrophysical matters and the development of data analysis techniques and algorithms will be undertaken at the University of Wales.

1. Introduction

The detection and study of gravitational radiation will be of great scientific importance. It will open up a new window on the Universe through which may come unique information about a variety of astrophysical systems – supernovae explosions, pulsars and coalescing compact binary stars. It is also possible that totally unexpected discoveries will be made, in much the same way as has occurred in radio and x-ray astronomy. Detection will allow direct tests of some aspects of general relativity, which should help to distinguish between rival relativistic theories of gravity.

Many years of development work on prototype detectors, mainly in Germany, the UK and the USA, have produced insight in the relevant noise sources and how to overcome them in the quest for yet higher sensitivities in full-sized detectors. These studies gave rise to a number of technological spin-offs and have been of considerable interest to the general public.

Following these developments and intensive feasibility studies, three large detector systems have been funded worldwide. Two of these – forming the LIGO project [2] – will be in the USA, one situated in Washington State and the other in Louisiana; both detectors are to have arm lengths of 4 km. The other funded project – the French/Italian VIRGO project [3] – will have arms of length 3 km and is to be built near Pisa. These instruments are expected to be operational in their initial configuration in about six years' time. Development work is also being undertaken in Japan (100 m prototype) and Australia, in both countries with the long term goal of constructing detectors of 3 km arm length.

The original German-British project [4] – later known as GEO – proposed and agreed in principle in the UK in 1990, and ranking high in the list of projects to be funded in Germany, was cancelled in 1991 due to lack of funding in both countries.

In this paper we discuss a new advanced detector project of 600 m arm length – GEO 600. The detector [1], a four-pass delay line system, with power and signal recycling, should have a sensitivity close to those expected for the first LIGO and VIRGO interferometers, over part of their frequency range.

2. Astrophysical aims

2.1. Long-term aims

The overall target of all the gravitational wave detector projects is the detection and study of gravitational wave fluxes and waveforms from various astronomical sources. The strength of a gravitational wave signal can be characterised by the strain in space at a detector, the gravitational wave amplitude h being defined as twice this strain.

For example, observations over a year of coalescing binary systems of neutron stars or black holes with a detector capable of detecting bursts with an amplitude of around 10^{-22} would provide crucial information about neutron star masses and binary evolution. If three or more detectors see such an event, its location on the sky and its distance can be measured, allowing a high-accuracy determination of the Hubble constant [5], and giving definitive information about whether gamma-ray bursts originate in such binaries. If *four* detectors see an event, this would allow the spin 2 nature of the graviton to be definitively checked. Optical and gravitational observations of a supernova could allow the relative speed of gravitational waves and light to be tested to approximately 1 part in 10^9. Cross-correlations between two detectors would either detect background stochastic gravitational waves or decrease by 5 orders of magnitude the current upper limit on their energy density. This could put tight constraints on theories of galaxy formation. Pulsars could be searched for by integrating over times of several months, and one might expect one or more detectable pulsars in our galaxy today if 1% of all neutron stars were born with rotation periods of 2 ms or less, and with symmetries allowed by current theory and observation. The recent detection of a 2.1 ms pulsar in SN 1987A suggests that this is a relatively conservative estimate. Moreover, the pulsar PSR J0437-4715 discovered in 1993, at a distance of 100 pc and having a rotation frequency of approximately 173 Hz, could be expected to produce a signal of amplitude up to 3×10^{-26} at ~ 346 Hz. Similar techniques might detect a rapidly spinning neutron star rotating at the Chandrasekhar-Friedman-Schutz (CFS) instability point.

2.2. Immediate detection aims

The present paper addresses the development of detectors to the sensitivity that is called "Stage-1" by LIGO, roughly the ability to detect a 1 kHz burst with a sensitivity of 10^{-21}. If the proposed detector is built, then with the two LIGO and one VIRGO first-stage detectors there will be a network of 4 such detectors of comparable sensitivity around the world. Although source predictions at this level are less certain than at the level of 10^{-22} that was assumed in the previous section, there are some very exciting possibilities.

Interestingly, since the time the original GEO/LIGO/VIRGO proposals were written some five years ago, a number of astrophysical developments have made strong gravitational waves seem much more likely for some sources.

2.3. Some possible target sources

Sources that could be targeted by the network of 4 detectors include:

Strong bursts from supernovae. It is increasingly clear that there is a large variety of supernovae, and many low-luminosity ones (like SN 1987A) are missed in surrounding galaxies. Computer simulations are still not able to predict realistically what will happen in a gravitational collapse with high angular momentum, which is the situation likely to lead to gravitational radiation. Until recently, the assumption has been that rotation was not important: all young pulsars, like the Crab, are relatively slowly rotating.

However, the unpublished observations by Middleditch *et al.* [6] of a 467 Hz optical pulsar in SN 1987A, spinning down on a time-scale less than 10^5 yr, show that, contrary to this prejudice, rapid rotation may be common or even normal [7] in gravitational collapse. The rapid spin may be associated with the unusually low optical brightness of this supernova, and may indicate that a substantial population of supernovae with rapidly rotating cores has been missed in supernova statistics. This would greatly increase the likelihood of strong bursts of gravitational waves, detectable even if they came from the Virgo Cluster by first-stage detectors. The event rate could quite plausibly be several per year.

Moreover, pulsar evidence [8] now suggests that the mean space velocity of pulsars is three times higher than had previously been estimated: typical speeds are 450 km/s. This linear velocity must come from some non-axisymmetric asymmetry in the gravitational collapse, and this would also enhance one's expectations of gravitational radiation. If this velocity is acquired on the timescale of the bounce, 1 ms, then the *minimum* amplitude of gravitational radiation would be about 5×10^{-21} for a supernova at 1 kpc. Of course, if the collapse is messy and non-symmetric, the radiation would be expected to be much stronger than this.

Coalescing binary systems. Observations of pulsars like the Hulse-Taylor pulsar PSR 1913+16 have suggested that the nearest such system that will actually coalesce within any year will be about 100 Mpc away. This would be easily detectable by the Stage-2 detectors, with their higher sensitivity and (importantly) better performance at low frequencies; but until recently such events seemed out of the reach of first-stage detectors. However, theoretical studies of binary evolution [9, 10] have recently suggested that there should be a large population of very tight neutron-star binaries that have such short gravitational-wave-inspiral times. The times are so short that the chances of seeing one at any particular time in our Galaxy are small, but the coalescence rate integrated over time in our Galaxy could be at least 100 times larger than before. That would move the nearest such coalescence in one year in to about the distance of the Virgo Cluster, where it might well be detectable by Stage-1 detectors, including GEO 600.

Pulsars and accreting neutron stars. If the newly discovered nearby pulsar, PSR J0437-4715, radiates gravitational energy at a rate comparable to the rate at which it is losing rotational energy (as inferred from its spindown), then it would produce a signal of amplitude up to 3×10^{-26} at 346 Hz. This should be detectable by GEO 600 in a year of observing. Significantly, the new pulsar in SN 1987A is spinning down much more rapidly, and would radiate at $h \sim 1.4\times10^{-26}$ at 934 Hz on the same assumption; this might also be detectable. In the case of SN 1987A, the assumption that the radiation of gravitational waves is the dominant energy loss is not unreasonable: the magnetic field may well be weak at present, and there could still be significant irregularities in the shape of the star if it were formed in a rapidly rotating collapse. Moreover, the SN 1987A pulsar also raises the possibility that there are nearer pulsars, formed by weak supernovae in our Galaxy, that could still be strong radiators. These might be found by doing wide-band gravitational-wave searches of particular regions of the galactic plane in a year-long data set.

Stochastic background. The detection of a cosmological background of gravitational waves would be one of the most significant events in astrophysics since the detection of the cosmic microwave background. There have been no recent developments to suggest that the cosmological gravitational wave background at frequencies above 100 Hz should be any larger than we estimated in the original GEO proposal in 1989. However, searches will certainly be made with Stage-1 detectors, and it is likely that GEO 600 will be able to do a better job with the VIRGO detector than the two LIGO detectors could do at Stage-1. The reason is proximity: to get a good correlation, detectors should be as close together as possible, so that they respond to the same (random) gravitational waves at the same time. The separation of the two LIGO detectors is more than 3 times greater than the separation of GEO 600 and VIRGO, leading to the loss of a factor of about 10 in sensitivity to energy density. It is unlikely that at Stage-1 the LIGO detectors could completely overcome this disadvantage with improved sensitivity or wider bandwidth.

The two European detectors will be likely to set limits on the ratio $\Omega_{\rm gw}$, of the energy density of the gravitational wave background to the closure density, of around 10^{-6} at 300 Hz. This is comparable to limits set at very low frequencies (sub-μHz) by observations of millisecond pulsars, and will allow the testing of some of the predictions of cosmic string theory.

Tests of gravitation theory. The direct detection of gravitational waves will, of course, be a momentous event in physics, and GEO 600 could well allow Germany and the UK to be part of it. But beyond this, the observation of gravitational waves provides significant information about gravitation theory. If a supernova in VIRGO is detected, then the delay between the arrival of the gravitational waves and the light signal tests the speed of gravitational waves. The light should lag behind the gravitational radiation by no more than about 1 day, due to the propagation of the shock in the star. This uncertainty, over a travel time of about 60 Myr, tests the relative speeds to one part in 10^9 or better.

Another fundamental aspect of gravity research is the question of polarisations other than those predicted by general relativity. These would indicate other spin fields, such as scalar fields, which have lately been the subject of renewed speculation from the point of view of unified field theories involving gravitation. Present limits on the couplings of other fields are about 10^{-3} of standard gravity. A gravitational wave observed by *four* detectors would have enough redundant information to provide an independent test of these couplings. *Without GEO 600, there is little prospect that such a test can be performed.* If the source were strong enough, such as a gravitational collapse in our galaxy, then it would be possible to improve present limits on additional gravitational fields.

2.4. Future developments

Exciting as some of these possibilities are, it must be stressed that, at the sensitivity levels of initial experiments, detection of gravitational wave signals cannot be guaranteed. Therefore, a further valuable aspect of the 600 m detector would be its use as a development system for later, more sensitive detectors. It is possible that the 600 m detector could have its sensitivity, particularly for narrow band sources, considerably enhanced by cooling of the detector test masses to reduce thermal noise and by optimising the design of the laser interferometry used. The initial design of system will allow for such later developments.

3. Required detector performance

To achieve all the detection aims mentioned above, a sensitivity of 10^{-22} over a bandwidth of approximately 1 kHz, or a sensitivity spectral density of $3\times10^{-24}/\sqrt{\mathrm{Hz}}$ from about 100 Hz is likely to be required; however the initial aims of the LIGO and VIRGO detectors are somewhat more modest than this – a few times $10^{-23}/\sqrt{\mathrm{Hz}}$. Initial coincidence experiments, likely to last several years around the end of the century are proposed to be at this level. Increasing the sensitivity will require the development of more advanced detectors and at present this is planned as a second stage for both LIGO and VIRGO requiring further development work to be funded.

We believe that a detector with shorter arm length (600 m) using more advanced techniques than are currently proposed for LIGO or VIRGO could achieve a sensitivity close to their initial sensitivities (at least above 200 Hz and possibly within a limited bandwidth) and on a timescale similar to or somewhat earlier than these detectors. The modest scale of GEO 600 will make it easier to introduce the sophisticated technology required. The building of such an instrument could allow a more sensitive coincidence experiment to be carried out in the early stages of operation of the long detectors. Furthermore such a detector could by itself carry out a meaningful search for gravitational radiation from nearby pulsars.

The design of interferometer developed for GEO 600 would be a very strong candidate for installation in the LIGO and VIRGO instruments at a later stage to allow these systems to attain their advanced target performance.

4. Proposed joint German/British 600 m detector – GEO 600

Based on many years of development work and collaborative efforts at the University of Glasgow and the Max-Planck-Institut für Quantenoptik, with strong theoretical support from the University of Wales (Cardiff), the research groups in Hannover, Garching, Glasgow and Cardiff are jointly proposing to build a gravitational wave detector using laser interferometry to sense the motion of essentially free test masses which form two perpendicular arms of length 600 m. This instrument will be built on farmland owned by the University of Hannover and available immediately for this purpose. The detector will be built just below ground.

4.1. Vacuum system

The vacuum system designed by J.R.J. Bennett from RAL will consist of a cluster of up to 9 stainless steel vacuum tanks each of 1 m diameter at the centre of the system and one tank of the same diameter at each end of the perpendicular arms. The end tanks will be joined to the cluster at the middle by stainless steel vacuum pipes of 0.6 m diameter. The system will be pumped by a combination of turbo molecular pumps and NEG pumps. The design will provide a vacuum pressure close to 10^{-8} mbar for H_2 and 10^{-9} mbar for other heavier gases, this being adequate for the design sensitivity of the instrument.

4.2. Interferometer arrangement

Various optical schemes for the interferometer are possible. However, at present it seems likely that a delay line interferometer with four passes in each arm will be installed, as a somewhat simplified version of the original delay line interferometer [4] proposed for the 3 km GEO detector.

Power recycling will be implemented to allow a standing power at the beamsplitter of approximately 6 kW, a figure consistent with the need to avoid excessive distortion of the optical phase fronts due to heating effects mainly in the beamsplitter (based on Winkler *et al.* 1993 [11]). Signal recycling as proposed by Meers (1988) [12] and demonstrated experimentally by Strain and Meers (1991) [13] will be used to increase the storage time of the system for the signal sidebands and so increase the detected signal size in the interferometer.

The input laser power will be approximately 5 W from a stabilised all-solid-state diode-pumped Nd:YAG laser system currently being developed at the Laser Zentrum Hannover (Golla *et al.* 1994 [14]). The excess noise due to relaxation oscillations in such lasers and its relevance for gravitational wave detectors has been studied by Campbell *et al.* (1992) [15] and the necessary reduction in such noise by electronic feedback has been demonstrated by Rowan *et al.* (1994) [16] and by Harb *et al.* [17]. The laser will be frequency prestabilised to a small optical cavity. The main beam will have its direction, beam diameter and convergence stabilised by passing through two in-line mode cleaning cavities of the type originally proposed and implemented by Rüdiger *et al.* (1981) [18]. The interferometer will be locked on a null fringe using techniques partly outlined in the original German/British proposal [4] and taken further in an experimental demonstration on a table top by Strain [13]. These locking techniques are currently being implemented in the suspended-mass 30 m prototype at Garching.

It should be noted that this optical system makes full use of the very low-loss mirror coatings and specially developed low absorption fused silica substrates that are now available. Achieving the required signal storage time with only a small number of bounces and a high degree of signal recycling has advantages over a conventional design, because it gives the detector tunability for narrowband sources and makes it highly immune to optical aberrations [19].

The beamsplitter, and the test masses that form the main mirrors of the interferometer, will consist of solid cylinders of fused silica, approximately 25 cm diameter and 15 cm thickness, with supersmooth and dielectrically coated surfaces. The recycling mirrors will be similar. The coatings will be of laser gyro quality, resulting in optical losses of only a few parts per million.

4.3. Seismic isolation, position and orientation control of test mass

The test masses in the interferometer will be isolated from ground motions using a multilayer stack of heavy metal and neoprene or silicone rubber. In order to prevent contamination of the mirror surfaces by impurities it is important that only a negligible surface area of rubber is exposed to the vacuum system. The rubber will therefore be encapsulated in very soft metal bellows which will be pumped separately from the rest of the system. Each test mass, the beamsplitter, and each recycling mirror will be suspended on a double loop as the lower mass of a double-pendulum suspension. The upper mass will be suspended on a single loop to allow the orientation of the lower mass to be controlled by tilting and rotation of the upper mass. Another pendulum will be mounted with a reaction mass close to the upper mass to allow electronic damping and orientation control of the pendulum system. For certain of the test masses a second reaction mass will be suspended below the first one to allow direct electronic feedback to the position of the test mass itself. In most cases the forces required for control of position and orientation will be imposed by coil-and-magnet systems, but electrostatic systems may be used for those forces which have to be applied directly to the test masses. Experimental studies of multiple mass systems of a similar type have been carried out in Glasgow (Veitch *et al.* 1993 [20]), and systems of a similar type have been installed in the 30 m prototype at MPQ. Automatic alignment systems based on the technique demonstrated by Morrison *et al.* (1994) [21, 22] on the 10 m prototype interferometer in Glasgow, and now being installed in the 30 m prototype at MPQ, will be implemented to maintain optimum orientation of the principal optical components.

4.4. Thermal noise of pendulum and internal modes

A dominant noise source in laser interferometric detectors is expected to be thermal noise associated with the pendulum modes of the suspended test masses, with the violin modes of the suspension wires, and with the internal modes of the test masses.

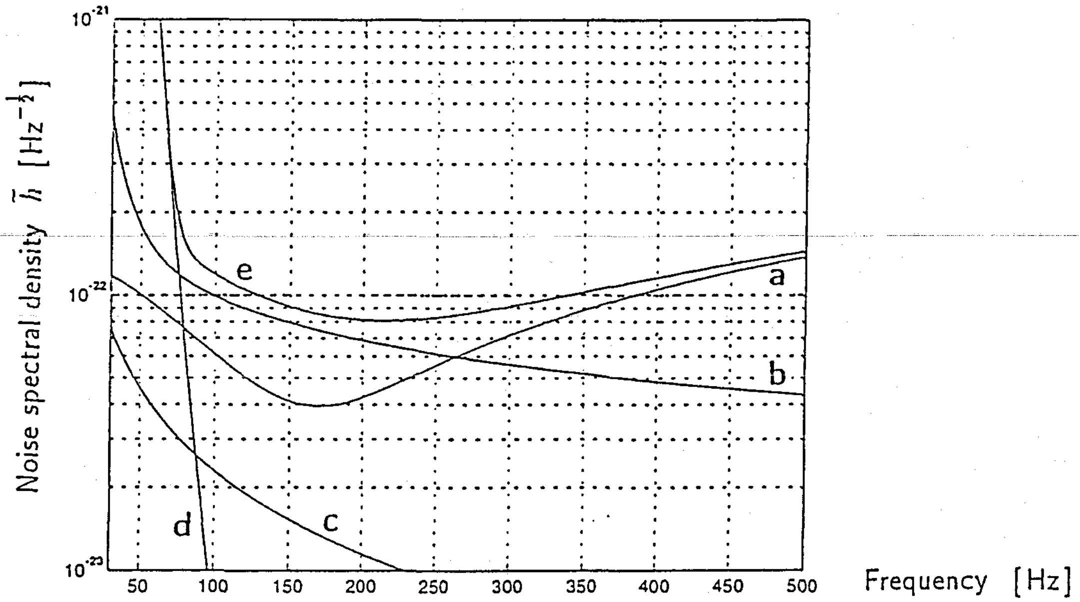

Figure 1: *Expected noise budget of the proposed* 600 m *detector. Curve* a *is the photoelectron shot noise for a 4 pass delay line illuminated with* 5 W *of laser light* (1.06 μm) *and typical mirror losses of* 20 ppm *per mirror. The system incorporates dual recycling, with a power recycling factor of* 2000 *and the signal recycling set to give relatively wide bandwidth. Curve* b *is the thermal noise in the system. The test masses are each* 16 kg, *of fused silica of* 25 cm *diameter and* 15 cm *thickness, as is the beamsplitter. The quality factors of the internal modes are taken to be* 5×10^{6} *and of the pendulums to be* 10^{8}. *Curve* c *represents the limit set by the Heisenberg Uncertainty Principle. Curve* d *represents a likely seismic noise limit for the sensitive components isolated by 4 layer stacks and suspended as double pendulums. Curve* e *is the overall noise spectrum of the proposed* 600 m *detector, obtained by the combination of limits in curves* a *to* d.

To minimise the thermal noise contributions in the bandwidth of interest, very high quality factors (Q), *i.e.* low losses, are required for the suspension wires and the test masses. It has recently been shown by Logan *et al.* (1993) [23] and independently by Gillespie and Raab (1993) [24] and by González and Saulson (1994) [25] that the Q factor of the simple pendulum mode is related to that of the suspension violin modes. Thus for very low suspension losses very high Q material must be used also for the suspension wires. It was also shown originally by Martin (1978) [26] and recently by Quinn *et al.* (1994) [27] that mechanical clamping of suspension wires or membranes leads to significant lowering of pendulum Q. Thus we intend to use a material of intrinsically high Q for the test masses and suspension wires (fused silica) and to avoid mechanical clamping wherever possible.

In our proposed interferometer the lower fused silica test masses will be suspended from upper masses, also of fused silica, on double loops of fused silica fibre. These will be welded or optically contacted to the fused silica masses in order to obtain very high Q for both the pendulum mode and the internal modes of the masses.

Test experiments by Martin (1978) [26] and more recently by Braginsky *et al.* (1993) [28] suggest that Q factors of 5×10^7 for the *pendulum mode* should be obtainable and experiments on silicon by Logan (1993) [29] and on fused silica by the VIRGO group [30] indicate that Q factors for the *internal modes* of the test masses of 5×10^6 should be achievable with such a system. It should be noted that as a result of the mechanical filtering action of the lower pendulum, thermal noise associated with the upper mass and its pendulum is not so important and thus a loop of steel wire may be used for its suspension.

4.5. Sensitivity to be achieved

In the interferometer system envisaged, the noise sources discussed above add up as shown in Figure 1. The noise is expressed as the *linear* spectral density of the apparent strain, $\tilde{h}(f)$. The assumptions made are given in the caption of Figure 1.

As becomes apparent, thermal noise from the suspension and the internal modes is expected to limit the sensitivity over a significant part of the frequency range (as shown in Figure 1). This is why cooling the test masses is an approach seriously to be considered. The proposed design does not preclude such a sensitivity-enhancing scheme.

5. Previous work in the field

Both the MPQ and Glasgow groups have carried out a large amount of development work over the last 15 years. The prototype detectors at Glasgow and MPQ Garching have achieved strain sensitivities of approximately $10^{-19}/\sqrt{\text{Hz}}$ over a kilohertz bandwidth and studies of many aspects of laser systems, suspensions, autoalignment techniques, mirror quality, and mirror heating and scattering problems have been tackled. New methods of improving the sensitivity of optical interferometers have been invented both at Glasgow and MPQ, and new laser systems of high stability and power have been developed at Hannover.

For a number of years the Cardiff group have been studying the characteristics of possible sources of gravitational waves. This work led to a significant programme of investigation of algorithms for searching for signals in noise, and also to the development of a powerful software environment for wide-ranging analysis of data from detectors.

The prototype detectors at MPQ and Glasgow were run in coincidence for 100 hours in 1989 with much of the data analysis undertaken by the Cardiff group. The results are currently being published (Nicholson *et al.* 1994 [31]). A significant result of this analysis is that the presence of a low rate of spurious pulses on the detector outputs had little effect on the sensitivity of the search for gravitational waves. In a search for a reported pulsar source, Niebauer *et al.* 1993 [32] developed an efficient algorithm with which the large volume of data was greatly reduced, thus opening the way for sophisticated searches even for unknown sources.

6. Future prospects

It is a particular feature of the proposed antenna that it lends itself to future modifications and enhancements. As mentioned earlier cooling of the test masses to approximately 20 K could be carried out with some added technical effort and extra cost and could allow considerably enhanced narrowband sensitivity for continuous sources such as pulsars. Furthermore, the optical systems developed would be excellent candidates for use in the next stages of LIGO and VIRGO.

7. Worldwide collaboration

The *detection* and quantative *measurement* of gravitational waves strongly depends on simultaneous monitoring by a number of antennas (at least two for detection, preferably four for measurement and source location). This need for international collaboration during development as well as later for data exchange has created a climate of amiable competition amongst the research institutes involved.

This proposal for the GEO 600 antenna has met with close interest and strong encouragement by the leaders of LIGO and VIRGO, and they have expressed their desire for mutual assistance in the development and use of the antennas.

8. Conclusion

The building of the GEO 600 interferometer would add another instrument of comparable sensitivity to the coincidence network formed by the interferometers at the other three sites (two in the USA, one in Italy). This would greatly enhance the chances of a coincident observation and increase the precision of directional information for any source detected. GEO 600 will also act as a useful testbed for some advanced interferometric techniques and will thus help with the development of higher sensitivity experiments in the future.

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LISA

Laser Interferometer Space Antenna for gravitational wave measurements

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Abstract

LISA (Laser Interferometer Space Antenna) is designed to observe gravitational waves from violent events in the Universe in a frequency range from 10^{-4} to 10^{-1} Hz which is totally inaccessible to ground based experiments. It uses highly stabilised laser light (Nd:YAG, $\lambda = 1.064\,\mu$m) in a Michelson-type interferometer arrangement.

A cluster of six spacecraft with two at each vertex of an equilateral triangle is placed in an Earth-like orbit at a distance of 1 AU from the Sun, and 20° behind the Earth. Three subsets of four adjacent spacecraft each form an interferometer comprising a central station, consisting of two relatively adjacent spacecraft (200 km apart), and two spacecraft placed at a distance of 5×10^{9} m from the centre to form arms which make an angle of 60° with each other. Each spacecraft is equipped with a laser.

A descoped LISA with only four spacecraft has undergone an ESA assessment study in the M3 cycle, and the full 6-spacecraft LISA mission is now a likely third cornerstone under the extension of the ESA Horizon-2000 programme.

Some of the figures presented in this report still reflect the design at the time of the ESA assessment study. But more recent developments, allowing significant reductions in mass, power, and cost, will be addressed in the closing section.

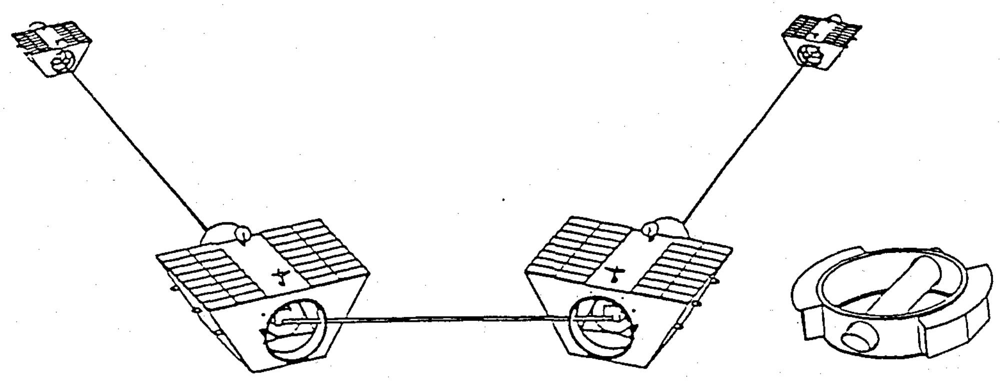

Fig. 1. *Configuration of a single LISA interferometer with four spacecraft. This earlier design of trapezoidal boxes was later changed into flat circular disks, their axes normal to the interferometer plane, as indicated for a single spacecraft (with top lid removed) on the righthand side.*

LISA

Laser Interferometer Space Antenna for gravitational wave measurements

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1. Overview

The goal of LISA (Laser Interferometer Space Antenna) is to detect and study low-frequency astrophysical gravitational radiation. The data will be used for research in astrophysics, cosmology, and fundamental physics. LISA is designed to detect the gravitational radiation from regions of the Universe that are strongly relativistic, e.g. in the vicinity of black holes. Such regions are difficult to study by conventional astronomy. The types of astrophysical sources potentially visible to LISA include galactic binaries of black holes, extragalactic supermassive black hole binaries and coalescences, and background radiation from the Big Bang. LISA will also observe galactic binary systems which are theoretically well-understood and observationally known to exist. Observation of these will provide strong verification of the instrument performance and a direct test of General Relativity.

LISA, with an array of six spacecraft, will measure such gravitational waves interferometrically. A single two-arm Michelson-type interferometer is formed from a vertex (actually consisting of two closely-spaced 'central' spacecraft), and two remote spacecraft defining the end-points of the arms, as indicated in Fig. 1 on the title page. The full six-spacecraft configuration, with two spacecraft at *each* vertex of an equilateral triangle, thus consists of three separate, but not fully independent, interferometers. This configuration provides redundancy against component failure, gives better detection probability, and it allows the determination of polarisation.

When a gravity wave passes by it causes a strain distortion of space. LISA will detect these strains down to a level of order 10^{-23} in one year of observation time, by measuring the fluctuations in separation between shielded proof masses located 5×10^6 km apart. The measurement is performed by optical interferometry which determines the phase shift of laser light transmitted between the proof masses. Each proof mass is shielded from extraneous disturbances (e.g. solar radiation pressure) by the spacecraft in which it is accommodated. Drag-free control servos enable the spacecraft to precisely follow the proof masses. Each interferometer has two symmetric arms in order to cancel out effects due to laser frequency noise. All spacecraft have a laser on board. The lasers in the two central spacecraft (which are 200 km apart) are phase-locked together, so they effectively behave as a single laser. The lasers in the end spacecraft are phase-locked to the incoming light, and thus act as amplifying mirrors. The relative displacement between the spacecraft and proof mass is measured electrostatically and the drag compensation is effected using proportional electric thrusters. Careful thermal design ensures the required mechanical stability.

2. The need for space-based detectors

LISA will complement the next-generation ground-based detectors (VIRGO, LIGO) by accessing the important low-frequency regime (10^{-4} to 10^{-1} Hz) which will *never*

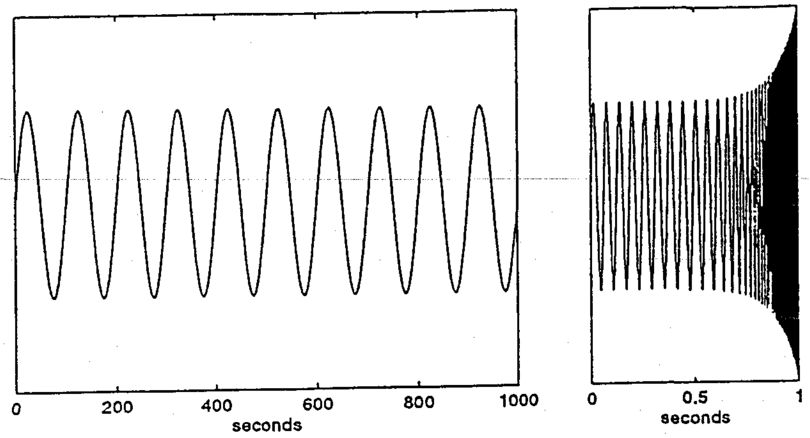

Fig. 2. *Two phases of binary coalescence. Left: early phase with very slowly changing frequency; right: rapidly rising frequency (chirp) before final merger.*

be observable from the Earth because of terrestrial disturbances. This low-frequency window allows access to the most exciting signals, those generated by massive black hole formation and coalescences, as well as the most certain signals, such as from galactic binaries. Ground-based detectors, on the other hand, are most likely to observe the rapid bursts accompanying the final stages of a compact binary coalescence. LISA would observe the 'low-frequency' epoch where the binary systems spend most of their life. Such a complementary scenario is depicted in Fig. 2. Note the widely differing time scales; the amplitudes are in arbitrary units.

Cosmic background gravitational radiation, which spans a wide frequency range, may be detectable. With comparable energy sensitivites, LISA and the ground-based detectors will, in combination, provide much extended spectral coverage, essential to test cosmological models.

3. Scientific significance

The expected scientific return can be appreciated from Fig. 3, which compares the sensitivity of LISA with the amplitudes of various gravitational wave sources.

Fundamental physics. LISA would *test gravitation theory.* Certain types of galactic binary systems, such as neutron star binaries, are so well understood that their radiation must be detectable. Failure to observe these signals would be catastrophic for General Relativity. By contrast, failure to detect gravitational waves from the ground would only upset current astrophysical models.

The rotation of the detector as it orbits the Sun will produce amplitude and phase modulation of the signal that will allow the source direction and polarisation to be determined. If coalescing binary supermassive black holes are seen (see below), their typical signal-to-noise ratio of several thousand will enable a very sensitive test for

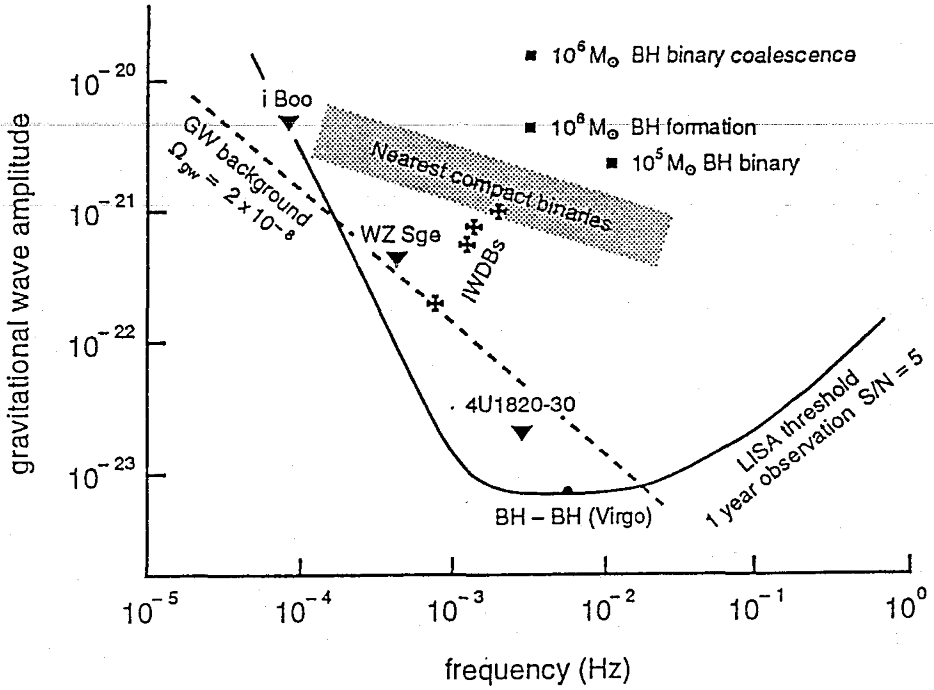

Fig. 3. *LISA measurement sensitivity compared with source strengths.*

auxiliary gravitational fields to be performed: scalar-tensor theories and alternative polarisation modes could be constrained much more severely than is possible by ground-based detectors. Gravitational waves from *cosmological background* will produce a noise in the detector which would dominate and hence be measurable if the energy density is about $\Omega_{\rm gw} = 2\times10^{-8}$ of the closure density, as predicted by cosmic string models (dashed line in Fig. 3). Such signals would be as important as the cosmic microwave background for our understanding of cosmology, and would give us our *earliest information on the Universe,* arising in an epoch much earlier than that of the microwave background.

Galactic astronomy. LISA would be guaranteed to find hundreds, or even thousands, of *neutron star binaries*, and very probably detect *cataclysmic variables* and *close white dwarf binaries* (shaded region in Fig. 3). The white-dwarf binaries are difficult to detect in any other way, yet they tell us much about stellar evolution. If their abundance is close to the current observational upper limit, the background due to extragalactic close white dwarf binaries unfortunately could be similar to the possible GW background curve shown in Fig. 3, and would interfere with the detection of some other interesting types of sources. However, the abundance of such binaries may well be substantially lower. In any case, the statistics of the *white dwarf* and *neutron star binaries* can be determined in an unbiased way. *Interacting white dwarf binaries* (crosses in Fig. 3) present many puzzles; gravitational wave observations will unambiguously determine their orbital periods. *Binary black holes* of $10M_\odot$ would be seen as far away as the Virgo cluster, where there should be at least one at a detectable frequency.

Extragalactic astronomy. The ideas that many galaxies (including our own) contain massive black holes, and that mergers of galaxies were common in the past, are gaining widespread acceptance. There is even evidence of binary black hole systems; an example is 3C66B which shows a precessing jet. Mergers of galaxies should produce *mergers of their supermassive black holes,* and their gravitational waves would be detected wherever in the Universe the event occurred. Recent calculations suggest that the event rate might even be as frequent as once per month.

The signal-to-noise ratio is typically several thousand for $10^6 M_\odot$ black holes. Waves this strong might not only be useful in testing gravity, as remarked above, but may make an important contribution to fundamental cosmology. By monitoring the amplitude and phase of the merger waves while the detector rotates, both the direction and total amplitude of the waves may be determined. Then, if the direction can be used to identify the source of the waves within a known cluster of galaxies, the amplitude will give an independent distance measurement to the source. A single redshift measurement would then determine the *deceleration parameter* q_0, and hence the mean density of the Universe, and thus measure the total density of *dark matter.* Merging galaxies may also trigger the *formation of massive black holes,* since they may replicate conditions at the time of galaxy formation. These formation events would also be detectable and identifiable. They may also be common, even the dwarf elliptical M32 seems to have a black hole.

4. Experiment description

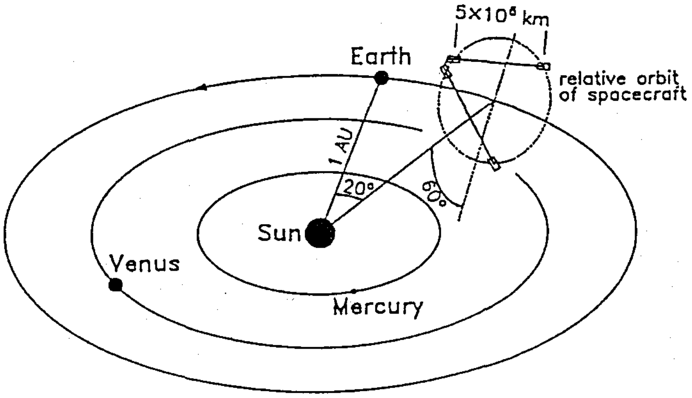

Fig. 4. *Proposed LISA orbit.*

A *single* LISA interferometer as shown in Fig. 4 consists of a V-formation of proof masses each shielded by a drag-free spacecraft. The vertex of the antenna's V-formation is formed by the two central spacecraft. In principle, one central spacecraft would be sufficient, but the optical system and attitude control requirements would be prohibitive. The four (6) spacecraft are in heliocentric orbits. They lie in a plane which is 60° to the ecliptic such that their relative orbit is a stable circular rotation with a period of 1 year. The 'constellation' should be located as far behind the Earth as possible (maximum of 20° due to launch vehicle constraints) to minimise Earth-induced relative velocities of the spacecraft which would lead to excessive Doppler-shifts of the transponded light. The two central spacecraft are 200 km apart, and the distance to the remote spacecraft, defining the interferometer arm length, is 5×10^6 km.

The payload module is indicated as a cross-sectional view in Figure 5. It consists of the inner structural carbon-epoxy cylinder with four stiffening rings, surrounded by a carbon-epoxy payload thermal shield cylinder. The thermal shield, cut at a 30° angle at both sides, keeps sunlight from the thermally stable payload interior throughout the heliocentric orbit. The payload cylinder houses four major assemblies: the telescope assembly, the optical bench, the preamplifier disk and the radiator disk.

The telescope assembly contains a 38 cm diameter f/1 Cassegrain telescope. The primary mirror is a double-arch light-weight ultra-low expansion (ULE) design. The secondary is supported by a three-leg carbon-epoxy spider. The final quality of the plane wavefront leaving the telescope is $\lambda/30$.

The optical bench contains the laser beam injection, detection, and beam shaping optics, and the drag-free sensor (or "accelerometer"). The proof mass of the drag-free sensor acts as the mirror at the end of the interferometer arm. The bench consists of a solid ULE plate to which all components are rigidly attached. Light from the laser is delivered to the optical bench by a single-mode fibre. About 1 mW is split off the 1 W main beam to serve as the local reference for the heterodyne measurement of the phase of the incoming beam from the far spacecraft. Also, about 1 mW is split off and directed towards a triangular cavity which is used as a frequency reference.

The incoming light from the telescope is reflected off the proof mass and superimposed with the local laser on the phase measuring diode. On the two central spacecraft, a small fraction (a few mW) of the laser light is reflected off the back of the proof mass and sent for phase-comparison with the other central spacecraft via the steerable aft-mirror. The mirror is servoed using the signal from an auxiliary quadrant photodiode which senses the direction of the incoming beam from the other central spacecraft. By bouncing the laser beams off the proof mass in the manner described, the interferometric measurement of proof-mass position is, to first order, unaffected by motion of the surrounding spacecraft. This allows a relaxation of its relative motion specification (though the requirement on proof mass residual motion with respect to inertial space remains unchanged).

The preamplifier disk is a carbon-carbon structure with the accelerometer preamplifiers, the diode preamplifiers, and an ultrastable oscillator (USO) mounted on it. All other payload electronics are located outside the payload cylinder proper, on the spacecraft structure.

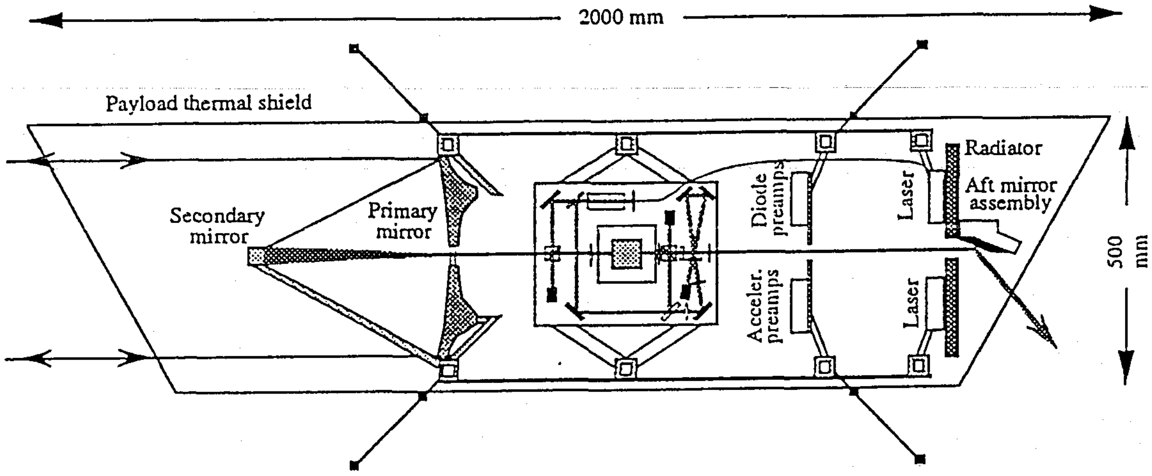

Fig. 5. *Cross-sectional view of one of six (identical) payload modules showing the telescope, the optical bench containing the drag-free proof mass (shaded square at centre), the preamplifiers on their mounting plate, and the lasers mounted on the radiator. The light paths are also indicated. The thermal shield is rotated 90°.*

The radiator disk (a carbon-carbon plate 40 cm in diameter and 1 cm thick) is designed to radiate away the heat ($\approx 20\,\mathrm{W}$) generated by the laser. The aft-mirror assembly, for communication between the near spacecraft, is attached to this radiator disk.

The laser consists of two monolithic ring YAG (yttrium-aluminium-garnet) crystals in series, each pumped by two laser diodes. The nominal single-mode output power is 2 W at a wavelength of 1064 nm. For LISA this has been downrated to 1 W to improve lifetime and aging properties. The operating temperature for the diodes and the YAG-crystal will be maintained by heaters. A complete spare laser will be carried.

The laser on one of the central spacecraft will serve as the master and will be locked to the onboard reference cavity. The laser on the other central spacecraft will be phase-locked to the master laser via the phase comparison beam exchanged between the two central spacecraft. The lasers on the central spacecraft can thus be considered identical, and the complete four-spacecraft setup behaves like a Michelson interferometer.

The position sensor for the drag-free control is derived from the GRADIO electrostatic accelerometer developed for ARISTOTELES. It contains a 4 cm cubic proof mass made of a gold-platinum alloy with magnetic susceptibility less than 10^{-6}. This proof mass is freely floating inside a gold-coated ULE cage which supports the electrodes for capacitive sensing of attitude and position. The ULE-box is enclosed in a vacuum-tight Ti-housing connected to the outside of the spacecraft by a tube to keep the interior of the accelerometer at a pressure of less than 10^{-8} mbar. Electrostatic charging of the proof mass due to cosmic ray protons with energies in excess of 100 MeV cannot be ignored. Active discharging is achieved by directing ultraviolet light from a mercury discharge lamp at the test mass and walls, similar to the approach proposed for GP-B.

Each payload module has a mass of 67 kg and a power consumption of 29 W dominated by 21 W for the laser.

5. Noise, Sensitivity

In the frequency range above 10^{-3} Hz, the LISA displacement noise level is below $25 \times 10^{-12}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. Below, down to 10^{-4} Hz, performance is limited by spurious accelerations. These consist partly of real accelerations (such as residual gas impacts on the test masses) and partly of several thermal distortion effects that also acquire a $1/f^2$ dependence in displacement (the leftmost sloping curve on the LISA sensitivity plot in Fig. 3). The displacement error is dominated by photon shot noise (the floor of the sensitivity plot in Fig. 3).

The spacecraft thermal model suggests a temperature stability of the optical bench of about $10^{-6}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ at 1 mHz. With an expansion coefficient of roughly $3\times10^{-8}/\mathrm{K}$ for ULE, this leads to a frequency noise of $10\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ for the laser. Assuming a 5000 km arm length difference after final orbit injection, this would lead to an unacceptably large apparent displacement noise. A laser phase noise correction scheme will be used that deduces the laser frequency fluctuations from the sum signal of the two interferometer arms, and then subtracts their effects out from the signal. For this technique, the arm length and the arm length difference need to be determined absolutely to about 1 km and 20 m, respectively. This is achieved by X-band radio tracking from the ground combined with laser phase information. The lasers on the end spacecraft will be phase locked to the incoming beam, thus acting as amplifying mirrors sending the light back to the central spacecraft.

Due to gravitational disturbances by Solar System bodies, the spacecraft will have a small but varying velocity relative to each other, causing a Doppler-shift of the returning beam on the order of 1 MHz. The signal cannot be telemetered to the ground due to data rate limitations. A local ultrastable oscillator (USO) is used to heterodyne the signal down to near DC. If the difference in the Doppler-shifts between the two arms is small enough, then the clock noise from the USO cancels. To use a flight qualified USO like the one on the Mars Observer with an Allan deviation of 2×10^{-13} would require the difference in arm length velocities to be smaller than 7 mm/s. This could be achieved by occasional manoeuvres of ΔV less than 100 mm/s using the electric thrusters with their accurately controllable thrust (next section).

Initial beam acquisition will rely on star trackers to align the spacecraft to better than 10^{-4} rad. The laser beam will then be defocussed from its diffraction-limited divergence and imaged in the receiving spacecraft on quadrant diodes and CCD arrays. Their signal will be used to iteratively repoint the spacecraft until the laser beam divergence can be reduced to the minimum value. Operational attitude control signals will be provided by the main signal detection diodes, the difference between the signals from their quadrants giving information on wave-front tilt. The pointing jitter is expected to be less than a few nrad/$\sqrt{\text{Hz}}$ which, for an outgoing wave front deformation of less than $\lambda/30$, leads to an apparent displacement noise less than the design goal.

Data processing to recover the gravity wave signals will involve standard spectral and matched filter analysis once the frequency noise has been removed by correlating the signals from the two arms. The spectral resolution from one year observation (3×10^{-8} Hz) coupled with a desired signal-to-noise-ratio of 5, led to the sensitivity curve shown Fig. 3.

6. Spacecraft design and mission analysis

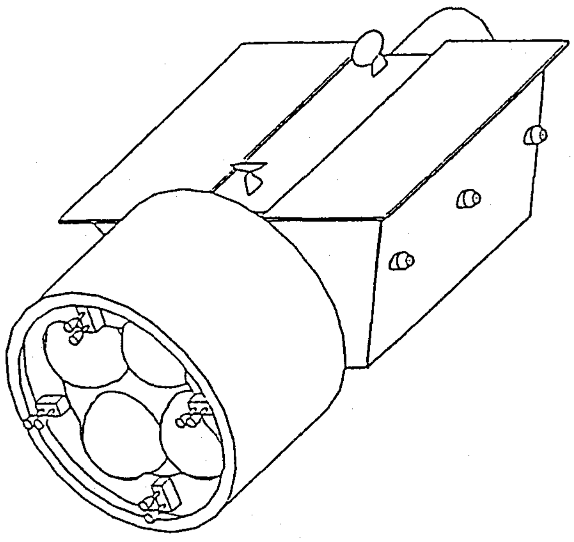

Fig. 6. *LISA spacecraft with propulsion module.*

A single interferometer with four of the six spacecraft is sketched as Figure 1 on the title page. All six spacecraft are identical. Figure 6 illustrates a single (earlier design) spacecraft attached to the jettisonable propulsion module. These spacecraft consist of a trapezoidal box around a central cylinder. The payload module (Fig. 5) is mounted inside the central cylinder with a system of Kevlar rods. Spacecraft and payload electronics boxes are mounted on the inclined side panels. Structural stability requirements dictate the use of materials with a low thermal expansion coefficient, so carbon-epoxy is used for the panels and central cylinder. The total mass for a single spacecraft is 300 kg. Control torques and forces for attitude and drag-free control are provided by the Field Emission Electric Propulsion (FEEP) subsystem, which can provide a controlled thrust in the range of 1 to 100 μN, with noise below 0.1 μN. Six clusters of four thrusters each are mounted on the inclined walls of the spacecraft.

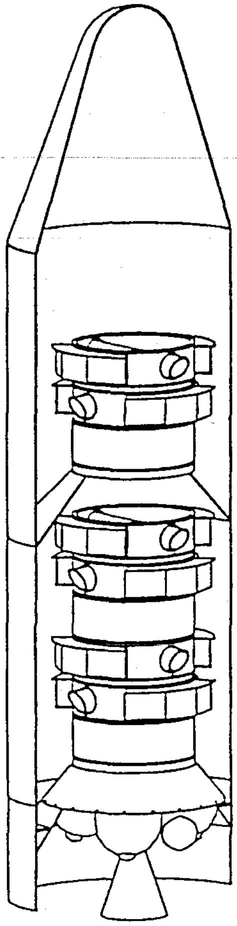

Fig. 7. *Ariane 5 dual launch configuration.*

An X-band telecommunications system provides the TT&C functions utilizing two (one redundant) 30 cm high-gain antennas to provide a telemetry data rate of 560 bps to the ground stations located at Perth and Villafranca. Antenna pointing mechanisms provide the required 2π coverage in azimuth. Two GaAs solar array panels provide 183 W of power. A propulsion module is attached to the spacecraft by a conventional clamp band system, and is jettisoned after operational orbit injection. It carries up to 380 kg of propellant, a battery and pyro electronics for the clamp band release, and the gyros providing rate information after separation from the launch vehicle and during orbit injection manoeuvres.

In order to maintain the spacecraft in a stable equilateral triangle (Fig. 4) with baselines of 5×10^6 km, an eccentricity (e) of 0.00965, and an inclination with respect to the ecliptic of $e/\sqrt{3}$ are required. Although the orbits are perturbed by planetary gravity, their initial elements can be chosen such that the arm-change rate will stay below 3.6 m/s over a 5-year period. If necessary, the data-gathering can be interrupted occasionally for orbit maintenance manoeuvres as mentioned in the previous section. The experiment demands a determination of the arm lengths to better than 1 km, and radio data, augmented by Doppler data from the on-board lasers, is required to obtain this orbit determination accuracy.

The six spacecraft will be launched by a single Ariane 5 in *dual launch configuration* with two sets of two spacecraft in the lower compartment, and one set in the upper, under the short fairing, as indicated (for a new spacecraft design) in Fig. 7. In this new design, the payload is housed in a relatively flat (70 cm high) cylindrical box whose axis is normal to the optical axis of the payload module.

For launch dates between April and October, Ariane 5 can deliver up to 6800 kg to the required Earth escape trajectory from which each of the six spacecraft will be transferred to its individual orbit within 16 months by two main manoeuvres with a total ΔV between 600 and 1200 m/s. In addition, at least two correction manoeuvres (20 m/s and 40 cm/s) will be required to deliver the spacecraft with the required high accuracy (position less than 10 km; velocity less than 3 mm/s) into their final operational orbits. The maximum achievable spacecraft–Sun–Earth separation angle is limited by the required propellant (i.e. wet spacecraft mass) to reach the final orbit, and hence by the launch vehicle performance. From the preliminary studies to date, assuming a single Ariane 5, a maximum angle of 20° (as in Fig. 4) is achievable. Efforts will be made to reduce mass in order to increase this separation angle.

7. Management, mission operations, archiving

The proposed procurement scheme for LISA is based on the concept that the payload will be provided by Principal Investigators (PIs) with funding from ESA's Member States as far as European contributions are concerned, and from NASA for possible US contributions. Payload selection would take place via the normal procedure which includes issue of an Announcement of Opportunity (AO), technical and scientific evaluation of proposals, and approval by the SPC.

ESA would be responsible for spacecraft procurement and system testing, launch and operations. A LISA Science Working Team comprising the PIs, the Experiment Manager, an ESA Project Scientist, and an ESA Project Manager would be established to direct the project. Nationally funded payload subsystems such as lasers, optical bench, telescope, accelerometer, and structure, will be constructed at PI institutes. One institute would peform the overall management, integration, and testing of the payload under the responsibility of an Experiment Manager who would be the single-point interface to the ESA Project Team.

The overall responsibility for the mission rests with the ESA Directorate of the Scientific Programme. Mission control will be the responsibility of the Directorate of Operations. The routine operational phase will be supported by the ground stations in Villafranca and Perth from where the data will be routed to the Mission Control Centre (MCC). The operations conducted from the MCC include scheduling and planning of spacecraft operations, monitoring and control of status and proper functioning of the spacecraft, and execution of flight control.

Upon receipt of the telemetry data in the MCC, the housekeeping packets will be analysed by the MCC in order to check the health of spacecraft and instruments. Payload housekeeping and science data will be forwarded from the MCC to the LISA Science Centre (LSC) located at a PI institute (to be selected through the AO), where the status of the payload will be monitored. Payload Doppler data will be immediately processed, and any desired manoeuvre commands will be sent to the MCC for uplinking. The LSC will calibrate the interferometer data and distribute them to the PIs. One year after receipt of the data, it will be sent to ESA's Space Science Department for archiving. This archive will serve the scientific community requesting access to the LISA data.

8. Recent Developments

A descoped LISA with only four spacecraft has been proposed for the M3 selection cycle of medium-sized missions. Of the 150 proposed missions, 7 were selected and underwent an assessment study in 1993/1994, and LISA was one of them.

A LISA mission with four spacecraft would be lost if one of the spacecraft is lost. This is also true for any mission with only one spacecraft. For small failure probabilities, the risk for LISA is in first order higher by only a factor of four. In any case, the baseline for the Cornerstone proposal assumes six spacecraft, whereby the loss of up to two spacecraft (not at the same vertex) could be tolerated without loss of the entire mission. In fact, this makes the mission more reliable than even a single spacecraft mission. Incidentally, with CLUSTER, there is a precedent for ESA to fly a multi-spacecraft misson with no backup, where the primary scientific goal would not be achieved in the event of a single-spacecraft failure.

The LISA M3 Assessment Study assumed four spacecraft in order to keep costs down. Using conventional technology, that mission was costed at 694 MAU. Preliminary assessments at ESTEC reveal that six spacecraft based on conventional technolgy can be accommodated in a single Ariane 5. Only three propulsion modules are required (two spacecraft per module) – not six. In combination, these factors suggest that a six-spacecraft mission need not be much more expensive than a four spacecraft mission.

More significantly, one can easily envisage that technological advances in the next 15 years will substantially reduce the mass and cost of various spacecraft and payload elements. The great potential of such a program can be demonstrated by some concrete examples:

1) Star trackers with a mass of 1.3 kg using 3 W of power are available now and could replace the 12 kg, 12 W star trackers assumed in estimates for this study.

2) There are transponders under development for flight in 1997 with a mass of 2 kg instead of 6 kg as assumed here.

3) Phased-array antennas with 1.5 kg mass could replace the 6 fixed antennas assumed for this study and this would save 9 kg and 10 W per spacecraft.

4) High voltage power supplies for the FEEP thrusters of 3 kg total mass could replace 41 kg assumed in M 3 studies.

The implementation of LISA as the third cornerstone, to be launched in the 2017 timeframe, is subject to a small increase in the ESA science budget starting in 2000.

In the more immediate future, funding should be available for technical research and development of the mission concept.

The table on the following page gives a summary of the LISA cornerstone mission, as of late 1994.

Table I. LISA Mission Summary

Objectives:	Detection of low-frequency (10^{-4} to 10^{-1} Hz) gravitational radiation with a strain sensitivity of $10^{-21}/\sqrt{\mathrm{Hz}}$. Typical sources are galactic binaries (black holes, neutron stars, white dwarfs), extra-galactic supermassive black hole formations and coalescences, and background gravitational waves from the Big Bang.
Payload:	Laser interferometry with electrostatically controlled drag-free reference mirrors housed in six spacecraft; optical arm lengths 5×10^6 km. Each spacecraft has two lasers (one spare) which operate together in a phase-locked transponder scheme. Diode-pumped Nd-YAG lasers: wavelength 1.064 μm, output power 1 W, Fabry-Perot reference cavity for frequency-stability of 3 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$. Quadrant photodiode detectors with interferometer fringe resolution of $10^{-5}\lambda$. 38 cm diameter f/1 Cassegrain telescope (transmit/receive) with $\lambda/30$ wavefront quality. Drag-free proof mass (mirror): 4 cm cube, Au-Pt alloy of extremely low magnetic susceptibility ($< 10^{-6}$); Ti-housing at vacuum $< 10^{-8}$ mbar; six-degree-of-freedom capacitive sensing.
Orbit:	Each spacecraft orbits the Sun at 1 AU. The inclinations are such that their *relative* orbits define a circle with radius 3×10^6 km and a period of 1 year. The plane of the circle is inclined 60° with respect to the ecliptic. On this circle, the spacecraft are distributed at three vertices, defining an equilateral triangle with a side length of 5×10^6 km (interferometer baseline). Each vertex has two closely-spaced spacecraft (200 km apart). This constellation is located at 1 AU from the Sun, 20° behind the Earth.
Launcher:	Ariane 5, dual launch configuration with two sets of two spacecraft in the lower compartment, and one set in the upper, under the short fairing. Each spacecraft has its own jettisonable propulsion module to provide a ΔV of 1000 m/s for final orbit injection. Annual launch window: April – October
Spacecraft:	3-axis stabilized drag-free spacecraft (six)
mass:	290 kg, *each spacecraft in orbit*
propulsion module:	216 kg, *two spacecraft per module*
propellant:	240–920 kg (depending on launch date), *for two spacecraft*
total launch mass:	6200 kg
power:	183 W, *each spacecraft in orbit*
Drag-free performance:	10^{-15} m/s^2 (rms) in the band 10^{-4} to 10^{-1} Hz achieved with 6×4 Cesium FEEP thrusters
Pointing performance:	few nrad/$\sqrt{\mathrm{Hz}}$ in the band 10^{-4} to 10^{-1} Hz
Payload, mass:	67 kg, *each spacecraft*
power:	48 W, *each spacecraft*
dimension:	diameter: 0.5 m, height: 1.7 m, *each spacecraft*
Telemetry:	560 bps continuous, *total for all six spacecraft* Ground stations: Villafranca (Spain), Perth (Australia)
Nominal Mission Lifetime:	specification 2 years; 3–10 years feasible