LISA
Laser Interferometer Space Antenna for gravitational wave measurements

presented by Jim Hough
Department of Physics and Astronomy, University of Glasgow
Glasgow, G128QQ, UK
(for complete list of authors refer to next page)

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.

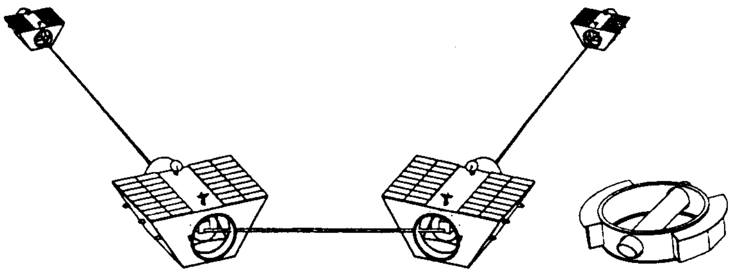

Fig. 1. *Configuration of a single LISA interferometer with four spacecraft. This earlier design of trapezoidal boxes was later changed into flat circular disks, their axes normal to the interferometer plane, as indicated for a single spacecraft (with top lid removed) on the righthand side.*

LISA

Laser Interferometer Space Antenna for gravitational wave measurements

The following report is largely based on an ESA Assessment Study undertaken in the early part of 1994. The LISA Assessment Report is available as document SCI(94)6, May 1994.

The members of the **Science Team** which carried out the study were:

P. Bender, Joint Institute for Laboratory Astrophysics, Boulder, Colorado, USA
A. Brillet, CNRS-LAL, Groupe VIRGO, Orsay, France
I. Ciufolini, Istituto di Fisica dello Spazio Interplanetario, CNR, Frascati, Italy
K. Danzmann, Institut für Atom- und Molekülphysik, Universität Hannover, Germany
R. Hellings, JPL, Pasadena, California, USA
J. Hough, Department of Physics and Astronomy, University of Glasgow, UK
A. Lobo, Departament di Fisica Fundamental, Universitat de Barcelona, Spain
M. Sandford, Rutherford Appleton Laboratory, Chilton, Didcot, UK
B. Schutz, Department of Physics and Astronomy, University of Wales, Cardiff, UK
P. Touboul, ONERA, Chatillon, France

They were supported in this study by three Working Groups:

Theory WG	**Accelerometer WG**	**Interferometry WG**
B. Schutz (Chair)	P. Touboul (Chair)	J. Hough (Chair)
A. Cavaliere	F. Barlier	R. Barillet
I. Ciufolini	P. Bender	A. Brillet
A. Lobo	A. Rüdiger	J. Faller
A. Polnarev	R. Schilling	W.M. Folkner
	T.J. Sumner	P. Gray
	H. Ward	L. Maleki
		D. Robertson
		R. Stebbins
		A. Tünnerman
		W. Winkler

ESA personnel involved in the study were:

J. Cornelisse	Study Manager; Future Projects Study Office, ESTEC
Y. Jafry	Study Scientist; Space Science Department, ESTEC
R. Reinhard	Fundamental Physics Missions Coordinator; Space Science Department, ESTEC 2200 AG Noordwijk, The Netherlands

Technical contributions by F. Hechler of the Directorate of Operations in Darmstadt, and by specialists of the ESA Technical Directorate at ESTEC are gratefully acknowledged.

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*

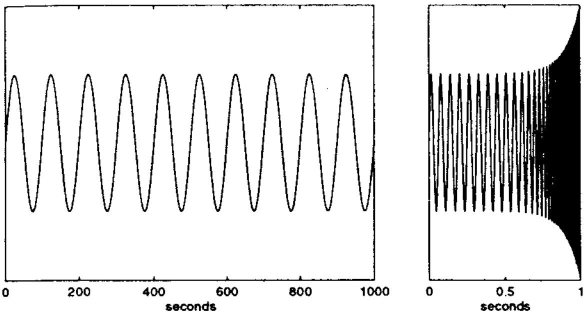

Fig. 2. *Two phases of binary coalescence. Left: early phase with very slowly changing frequency; right: rapidly rising frequency (chirp) before final merger.*

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

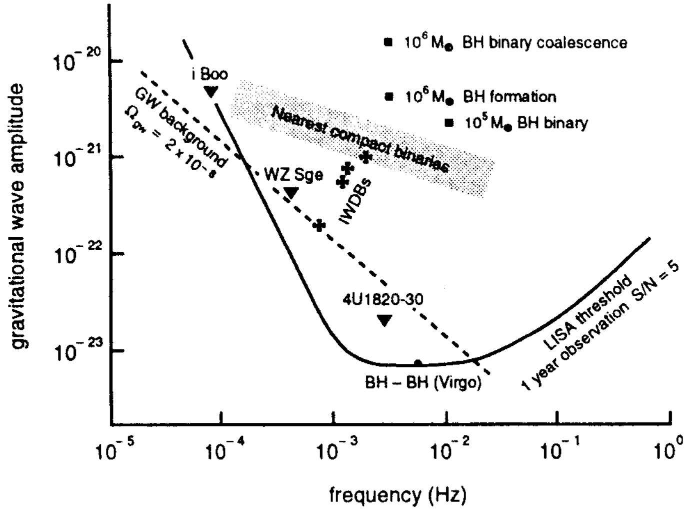

Fig. 3. *LISA measurement sensitivity compared with source strengths.*

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 $\Omega_{gw} = 2\times10^{-8}$ 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

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.

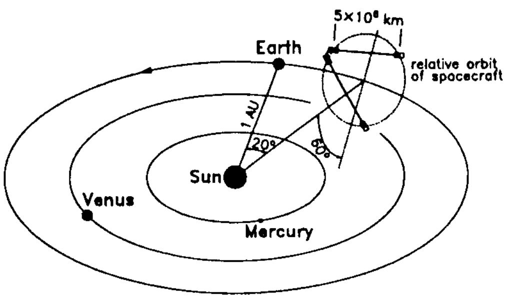

Fig. 4. *Proposed LISA orbit.*

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.

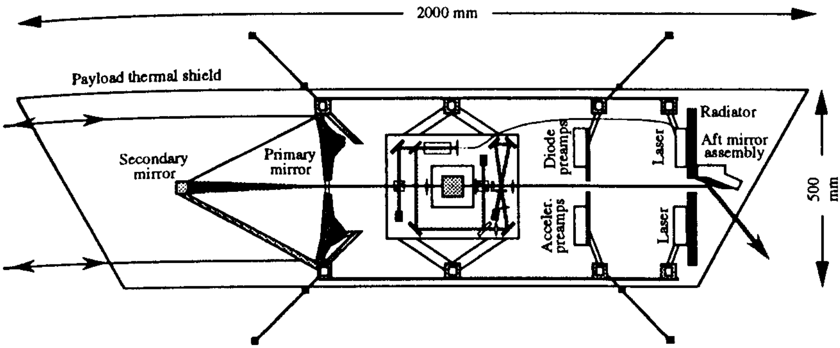

Fig. 5. *Cross-sectional view of one of six (identical) payload modules showing the telescope, the optical bench containing the drag-free proof mass (shaded square at centre), the preamplifiers on their mounting plate, and the lasers mounted on the radiator. The light paths are also indicated. The thermal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

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.

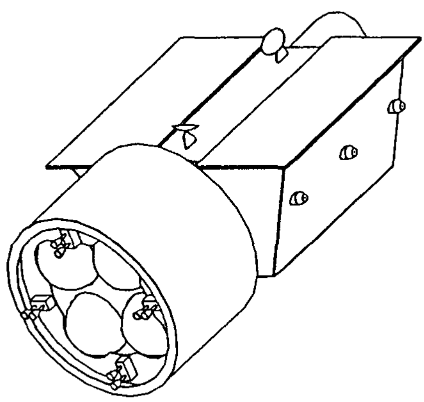

Fig. 6. *LISA spacecraft with propulsion module.*

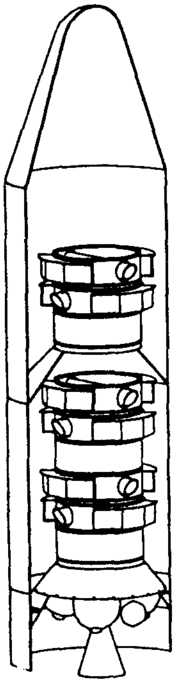

Fig. 7. *Ariane 5 dual launch configuration.*

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 $10^{-21}/\sqrt{\text{Hz}}$. 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 $\text{Hz}/\sqrt{\text{Hz}}$. 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/$\sqrt{\text{Hz}}$ in the band 10^{-4} to 10^{-1} Hz
Payload, mass:	67 kg, *each spacecraft*
power:	18 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