LISA: LASER INTERFEROMETER SPACE ANTENNA FOR GRAVITATIONAL WAVE MEASUREMENTS

W. M. Folkner, R. W. Hellings, L. Maleki
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
P. Bender, J. Faller, R. Stebbins
Joint Institute Laboratory for Astrophysics, University of Colorado, Boulder, CO, USA
K. Danzmann
Institute for Atomic and Molecular Physics, University of Hannover, Germany
J. W. Cornelisse, Y. Jafry, R. Reinhard
European Space Technology Research Center, Noordwijk, the Netherlands
A. Brillet, R. Barillet
CNRS-LAL, Groupe VIRGO, Orsay, France
I. Ciufolini
Institute of Interplanetary Space Physics, Frascati, Italy
J. Hough, D. Robertson, H. Ward
University of Glasgow, UK
A. Lobo
University of Barcelona, Spain
M. Sandford, P. Gray
Rutherford Appleton Laboratory, Chilton, UK
B. Schutz
University of Wales, Cardiff, UK
P. Touboul
ONERA, Chatillon, France
A. Cavaliere
University of Rome, Sapienza, Italy
T. Sumner
Imperial College, London, UK
A. Polnarev
Queen Mary and Westfield College, University of London, UK
F. Barlier
Observatory of Cote d'Azur, Grasse, France
A. Rüdiger, R. Schilling, W. Winkler
Max Planck Institute for Quantum Optics, Garching, Germany
A. Tünnermann
Lazerzentrum, Hannover, Germany

Abstract

The capability of observing gravitational radiation over a wide range of frequencies will open up major new opportunities in fundamental physics and astronomy. The Laser Interferometer Space Antenna (LISA) will be able to detect gravitational radiation over the frequency range from 0.1 mHz to 0.1 Hz with high sensitivity. Signals from hundreds to thousands of galactic binaries will be detectable. In addition, the coalescence of massive black hole binaries, which may have been produced by mergers of galaxies or of pregalactic structures, would be observable out to large redshifts. Such signals would allow the study of the interactions of large masses at small distances, which would not be possible in any other manner. LISA was proposed initially by a group of European and US scientists as a possible joint ESA/NASA mission, but has been studied recently as a candidate for a predominantly European mission. The results of the study indicated that the, technology for the mission is available or will soon be available. The main part of the study team report given here summarizes the scientific objectives and the mission concept.

Copyright © by the American Institute of Aeronautics and Astronautics, Inc All rights reserved.

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 which are strongly relativistic, e.g. in the vicinity of black holes. Such regions are difficult to study by conventional astronomy. The types of exciting astrophysical] sources potentially visible to LISA include galactic binaries of black holes, extra-galactic supermassive black hole binaries and coalescences, am-l 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 Relat ivit y.

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 5x1 0^6 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 dist urbances (e.g. solar pressure) by the spacecraft in which it is accommodated. Drag-free control servos enable the spacecr aft to precisely follow the proof masses. The interferometer has two arms (four spacecraft) in order to correct for laser frequency noise. Each spacecraft has 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. ~arC'fill thermal design ensures the required mechanical stability.

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 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.

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

Scientific significance

The expected scientific return can be appreciated from Fig. 1, which compares the sensitivity of LISA with the amplitudes of various gravitational wave sources.

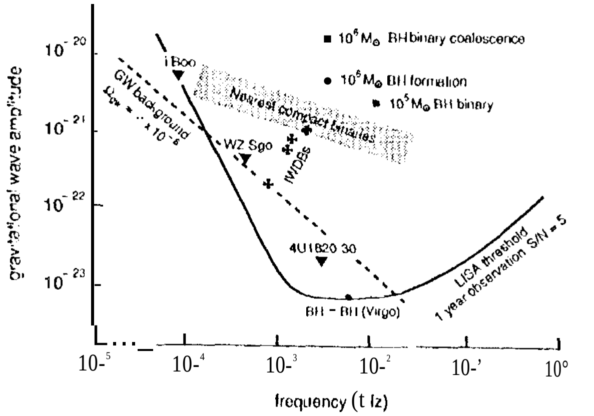

Figure 1. LISA measurement sensitivity compared with source strengths.

Fundamental physics

LISA would test gravitation theory. Certain 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 polarization to be determined. If coalescing binary supermassive black holes arc seen (see below), their typical signal-to-noise ratio of several thousand will enable a very sensitive test for auxiliary gravitational fields to be performed: scalar-tensor theories and alternative polarization modes could be constrained much more severe'ly than is possible by ground-based detectors. Gravitational waves from cosmological background 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. 1). 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 detect hundreds or, indeed, thousands of neutron star binaries and very probably detect cataclysmic variables and close white dwarf binaries (shaded region in Fig. 1). 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 tcr the current observational upper limit, the background due tcr galactic close white binaries unfortunately could be similar to the possible gravitational wave background curve shown in Fig.1, and would interfere with the detection of some other interesting types of sources. However, the statistics of the white dwarf and neutron star binaries can be determined in an unbiased way. interacting white dwarf binaries (crosses in Fig. "1) present many puzzles; gravitational wave observations will unambiguously determine their orbital periods. Binary black holes of 10 solar masses 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. l'here is even evidence of binary black hole systems; an example is 3C66B, which shows a processing 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 is typically several thousand for 10^6 solar mass 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 rrf 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.

Experiment description

The LISA interferometer (Fig. 2) consists of a V-formation of proof masses each shielded by a cfrag-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 optics] system and attitude control requirements would be prohibitive. The four spacecraft are in heliocentric orbits. They lie, in a plane which is 60° to the ecliptic such that the'ir 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 minimize Earth-induced relative velocities of the spacecraft leading 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.

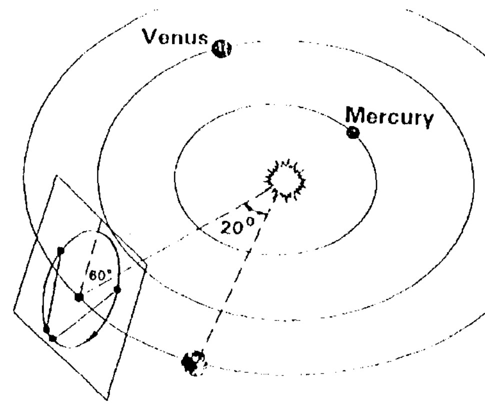

Figure 2. Proposed LISA orbits.

Fig. 3 shows a cross-section rrf a payload module. The structure consists of the inner structural carbon-epoxy cylinder with four stiffening rings, a thin carbon-epoxy payload thermal shield cylinder, and an outer calbcm-epoxy thermal shield. The thermal shields, cut at a 30° angle at the front, keep sunlight from the the'rma]]y stable payload interior' throughout the heliocentric orbit. At the rear, where the cylinder cannot be angled because there must be an orthogonal attachment with the propulsion module, direct sunlight is kept out by reflection from an internal conical mirror. The payload cylinder contains four major assemblies: the, telescope assembly, the optical bench, the preamp 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 carbc>n-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 dra~-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 fiber. 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

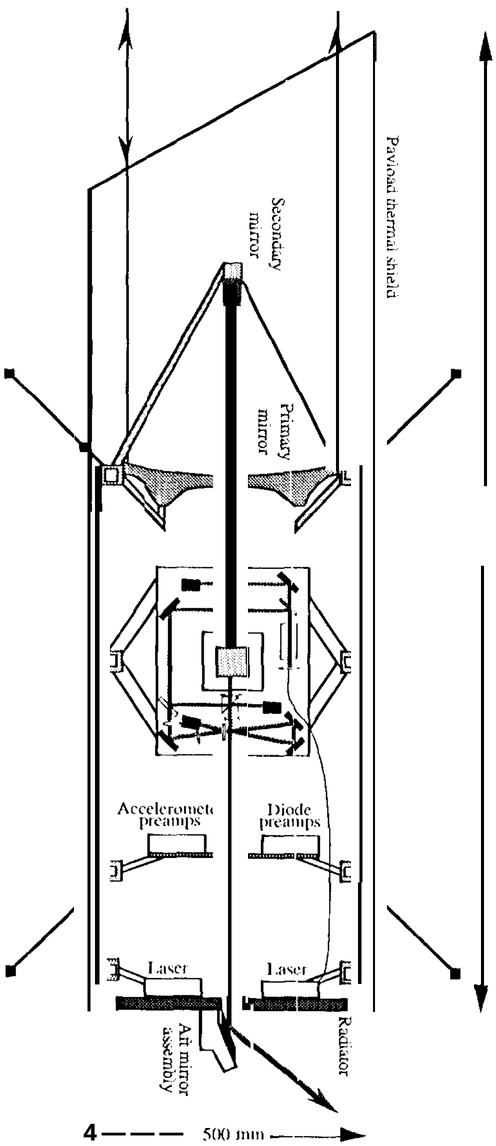

Figure 3. Cross-sectional view of one of four (identical) payload modules showing the telescope, optical bench containing the drag-free proof mass (shaded square at center), the preamplifiers on their mounting plate, and the lasers mounted on the radiator. The light paths are also indicated. The thermal shield is rotated 90°.

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 measurements of proof mass position is, to first order, unaffected by motion of the surrounding spacecraft. This allows a relaxation of the relative motion specification (though the requirement on proof mass residual motion with respect to inertial space remains unchanged).

The preamp disk is a carbon-carbon structure with the accelerometer preamplifiers, the diode preamplifiers, and an ultrastable oscillator (USO) mounted on it. All other electronics will be outside the payload cylinder. The radiator plate (a carbon-carbon disk 40 cm in diameter and 1 cm thick) is designed to radiate away the heat generated by the laser.

The laser consists of two monolithic ring YAG (yttrium-aluminum-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 drag-free position sensor is derived from the GRADIO electrostatic accelerometer developed for the proposed ARISTOTELES mission. 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 titanium 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 Gravity Probe B.

In the frequency range above 10^{-3} Hz, the LISA displacement noise level is below 25 pm/$\sqrt{\text{Hz}}$. 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. 1). The displacement error is dominated by photon shot noise (the floor of the sensitivity plot in Fig. 1).

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 setup behaves like a Michelson interferometer.

The spacecraft thermal model suggests a temperature stability of the optical bench of about $1 \mu K/\sqrt{Hz}$ at 1 mHz. With an expansion coefficient of 3×10^{-8}/K for ULE, this leads to a frequency noise of $10 Hz/\sqrt{Hz}$ 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 the solar system disturbances, 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 since the total data rate is limited to less than 100 bit/see. 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. Assuming a flight qualified USO like the one on the Mars observer with an Allan deviation of 2×10^{-13}, we would require the difference in arm length velocities to be smaller than 7 mm/s. This could be achieved by occasional maneuvers of less than 10 cm/s using the electric thrusters with their accurately controllable thrust (next section).

Initial beam acquisition will rely cm star trackers to align the spacecraft to better than 10-4 rad. The laser beam will then be de-focused from its diffraction-limited divergence and imaged in the receiving spacecraft on quadrant diodes and CCD arrays. Their signal will be used to iteratively re-point 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-ftont tilt. The pointing jitter is expected to be less than a few nrad/$\sqrt{Hz}$ 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 1 year observation (3×10^{-8} Hz) coupled with a desired signal-to-noise ratio of 5, led to the sensitivity curve in Fig. 1.

Each payload module has a mass of 67 kg and a power consumption of 48 W dominated by 18 W for the laser.

Spacecraft design and mission analysis

Fig. 4 illustrates a single spacecraft attached to its jettisonable propulsion module. Except for the laser phase comparison link between the two central spacecraft, the four spacecraft are identical. Each spacecraft consists of a trapezoidal box around a central cylinder. The payload module (Fig. 3) is mounted inside the central cylinder with a system of Kevlar rods. Spacecraft and payload electronic boxes are mounted on the inclined side panels. Structural stability requirements dictate the use of materials with a low value of the coefficient of thermal expansion, so carbon-epoxy is used for the panels and central cylinder. The total mass for a single spacecraft is 305 kg. Control torques and drag-free control forces 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 FEEP thrusters are mounted on the inclined side walls of the spacecraft.

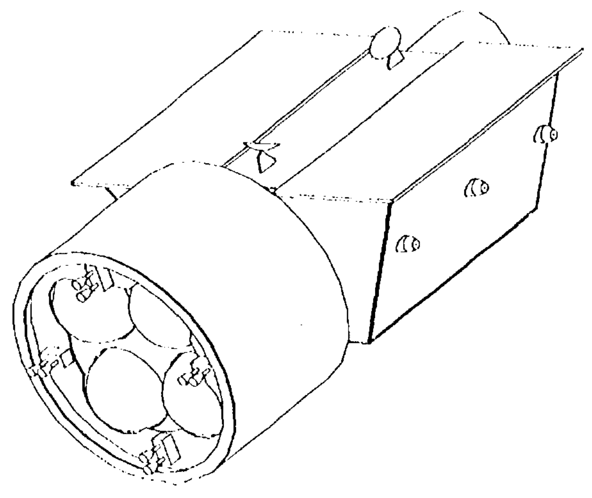

Figure 4. LISA spacecraft with propulsion module.

An X-band telecommunications system provides the telemetry, tracking, and command functions utilizing two (one redundant) 30 cm high gain antennas to provide a telemetry data rate of 375 bit/see 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 242 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 pyroelectronics for the clamp band release, and the gyros which provide rate information after separation from the launch vehicle and during orbit injection maneuvers.

In order to maintain the spacecraft in a stable equilateral triangle (Fig. 2) with baselines of $5x10^6$ 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 experiment can be interrupted occasionally for orbit maintenance maneuvers as mentioned in the previous section. The experiment demands a determination of the arm lengths to better than 1km, and radio data, augmented by Doppler data from the on-board lasers is required to obtain this orbit determination accuracy.

The four spacecraft will be launched by a single Ariane 5 in dual launch configuration with two space craft inside the SPELTRA (Structure Portense Externe Lancement Triple Ariane) and two spacecraft occupying the upper passenger compartment under the short fairing (Fig. 5). For launch dates between April and October, Ariane 5 can deliver 4100 kg to the required Earth escape trajectory from which each of the four spacecraft will be transferred to its individual orbit within 16 months by two main maneuvers with a total impulse, between 600 and 1200 m/s. In addition, at least two correction maneuvers (20 m/s and 40 cm/s) will be required to deliver the spacecraft with the required high accuracy (position uncertainty less than 10 km; velocity uncertainty 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. For the assessment phase, a separation angle of 20° was adopted (Fig. 2).

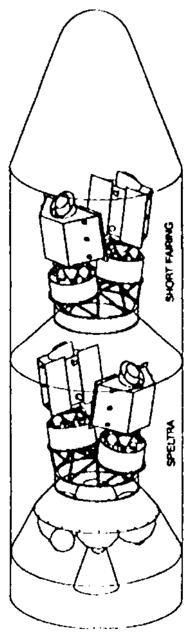

Figure 5. Ariane 5 launch configuration.

Acknowledgment

We would like to thank F. Hechler of the European Space Operations Center and W. Supper and other specialists of the European Space Technology Center for contributions to this report. Part of the research reported was performed by the Jet Propulsion Laboratory, California institute of Technology, under contract with the National Aeronautics and Space Administration.