A LASER INTERFEROMETER FOR GRAVITATIONAL WAVE ASTRONOMY IN SPACE


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Abstract

A space-based, laser interferometer for detecting gravitational waves could probe low frequency bands expected to be rich in gravitational signals. An interferometer of roughly 10^6 km path length could detect both the continuous periodic radiation from very many binary star systems and pulses which may have been emitted during galaxy formation.

Such an instrument has been proposed, and a preliminary design concept has been developed. In principle, it consists of a Michelson interferometer with the beamsplitter and the two end mirrors mounted on carefully shielded test masses inside three separate spacecraft. The cluster of spacecraft would follow 30° to 60° behind the earth in its orbit about the sun. The proposed interferometer is to be illuminated by a 1 W laser and will utilize 0.5 m optics. Many sources of noise have been analyzed, and a maximum strain sensitivity of 1 x 10^{-21}/√Hz is expected in the frequency range of 0.01 to 1 Hz.

The progress during the last two years reported here centers on refinements of the basic design parameters to increase the sensitivity of the antenna and on better estimates of various noise sources. In particular, the baseline laser power has been increased to reflect advances in continuous wave laser-diode-pumped Nd-YAG lasers. The distance of the proposed orbit from earth has been increased in order to reduce the secular orbital perturbations. Recent estimates of the noise from variations in the thermal radiation pressure gradient and cosmic ray impacts on the drag-free test masses are reported, and compared with noise from random molecular impacts.

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The Proposed Measurement

For several years, we have been refining a proposal to measure gravitational waves with a space-based laser interferometer. The goal is to probe low frequency bands for the expected continuous periodic radiation from binary star systems and for possible pulses from the era of galaxy formation. The baseline design concept and its analysis have been amended to reflect advances in technology and improved understanding of some of the noise sources. Here, we report some recent changes in the baseline design concept and analysis of noise sources.

The scientific motivation for the proposed measurement can be summarized as follows: The existence of gravitational radiation has been shown indirectly through the decay rate of the binary pulsar system. Direct detection is likely to be achieved by ground-based bar or interferometric antennas. With major efforts in seismic isolation and reduction of gravity gradient noise, these antennas may have usable response down to 1 Hz. The motivation for a space antenna would be a gravitational-wave survey of the $10^{-6}$ to $1$ Hz band. There, the many kinds of binary star systems are expected to contribute; the number of sources in our galaxy is so great as to form a continuum over part of the spectrum in an observation of any reasonable span. Pulses from the formation or collision of very massive black holes constitute a more problematic source of gravitational waves in this frequency band. However, the potential role of such events near the time of galaxy formation makes them astrophysically more interesting.

The general thrust of our design concept is to build a broadband detector which is optimized for the $10^{-5}$ to $10^{-1}$ Hz band. The instrument works in the same general manner as its terrestrial counterparts, that is, the passage of a gravitational wave is detected by measuring the changing separation of test masses with an interferometer. A space instrument has three essential advantages. It is free from the external gravity gradients and mechanical noise which limits ground-based interferometers to operate at higher bands. Interferometric antennas, in which the signal scales as the length and the noise is dominated by fixed end effects, can be made much larger in space than on Earth to achieve a higher signal-to-noise ratio. And, the test masses can be supported in a more nearly inertial manner, since they are in free-fall.

While the space environment may be free of the dominant terrestrial noise
sources, it has its own unique disturbances. There are also forces which compromise the free-fall condition. And, it has special demands on engineering and cost. Any strain measuring instrument which hopes to achieve a sensitivity of $10^{-21}/\sqrt{\text{Hz}}$ below 0.1 Hz will require careful design. What follows is the description of a space-based laser interferometer and the analysis of some of the noise sources which drive the design.

**Instrument Description**

Our antenna for gravitational-wave observations in space is a Michelson interferometer comprised of three satellites (Figure 1.). A central satellite carries the beamsplitter in a test mass, a laser transmitter and receiving equipment. The two end satellites carry reflectors in test masses and laser transponders. The end spacecraft are separated from the central spacecraft by $\sim 10^6$ km, and are 90° apart.

![Figure 1. Conceptual arrangement of an interferometer for gravitational observations in space.](image)

The preferred orbits place the three spacecraft approximately in the Earth's
orbit about the Sun, but trailing 30° to 60° behind the Earth. The trio would lie in a plane inclined 60° to the ecliptic. Inclinations, eccentricities and longitudes for their nodes and perihelia have been chosen so that their separation and relative orientation remain as constant as possible. Locations for the spacecraft have been selected to minimize secular perturbations from the Earth. It is important to make the separations nearly equal and approximately fixed. The extent to which they can be kept equal (for 30° behind the earth, about 6 parts in 10^6 over a 10 yr period) limits the fringe rate (~4 x 10^6 Hz) which must be tracked. Other closer locations, such as geosynchronous orbit, are possible, but with a considerable compromise in the sensitivity, and with serious ramifications in the environmental disturbances.

Although a space interferometer is freed of seismic noise, other environmental disturbances (e.g., solar wind, light pressure, etc.) demand that the test masses be enclosed in cavities which can shield them. Thus each spacecraft has a test mass moving freely inside a cavity, and which the spacecraft is servoed to follow. The critical optical component defining the optical path end—beamsplitter or reflector—is mounted in the test mass. For 10^6 km arm lengths, the acceleration exerted on the test mass by the surrounding spacecraft must be less than 2 x 10^{-18} g/√Hz in the band from 10^{-5} to 10^{-3} Hz in order to detect the continuous part of the spectrum due to binary systems in our galaxy. Potential sources of spurious forces are discussed below in the section entitled "Disturbances of the Test Masses".

The Triad satellite, flown in 1972, demonstrated a drag-free technology which reduced perturbations from 10^{-8} g to 5 x 10^{-12} g, integrated over all frequencies. Our goal for the integrated perturbations is also about 10^{-11} g, but the desired goal for the spectral density in the band from 10^{-5} to 10^{-3} Hz is far tighter. Integrating the allowable 2 x 10^{-18} g/√Hz perturbations over a 10^{-5} Hz bandwidth near 10^{-5} Hz frequency gives a level of only 6 x 10^{-21} g. Factors which make it possible to pursue such a tight disturbance goal are the much lower frequencies of most of the major perturbing effects in solar orbit and the smaller fluctuations in the forces on the spacecraft. However, much more detailed work is still needed on reliable methods for achieving the desired low disturbance levels.

Our current baseline design uses laser diode-pumped Nd:YAG lasers operating at 1 watt continuous, an order of magnitude increase over our previous expectations. These lasers are reliable, stable, efficient and compact. The laser
stability can be improved by locking it to an external cavity. Amending our baseline design for an order of magnitude increase in laser power has improved our sensitivity in the spectral region where the antenna is shot noise limited (10^{-3}-10^{-1} Hz). The interferometer actually relies on a laser transponder scheme where a local laser at the end spacecraft is phase-locked to the incoming beam and returned to the central spacecraft.

The two end satellites carry identical payloads. We envision a 0.5 m telescope with secondary supported by a graphite-epoxy truss. The incoming light is concentrated by the telescope and relayed to the test mass in its drag-free chamber. After reflection, the beam acts as the phase reference for the local transponder laser. The local transponder includes the external cavity stabilization system. All of the optics are mounted on a rigid, stable optical bench, constructed of graphite-epoxy. The electronics and housekeeping gear, such as power, propulsion and communication systems, are sequestered in an isolated section of the spacecraft. The entire spacecraft is wrapped in a carefully designed thermal shield to reduce thermal gradients and transients. The test masses in Figure 1 are shown as cubical in shape, but spherical test masses which are spun about the normal to the ecliptic may turn out to be more desirable.

The central spacecraft is considerably more complex, and its design is not as well determined. For example, the conceptually simple Michelson geometry with a beamsplitter mounted in the test mass is replaced by two separate Michelson interferometers fed from the same laser, with the beamsplitters attached to the spacecraft but with one end reflector of each interferometer on the same test mass. The apparent variation in the sum of the lengths of the two arms which are in the frequency range of 10^{-5} to 1 Hz would be interpreted as due to fluctuations in the laser wavelength, since unmodeled planetary perturbations will be very small for such frequencies. The corrected wavelength as a function of time would be used in analyzing the difference in length of the arms to detect gravitational waves.

Error Sources

Every precision measurement requires a careful analysis of the sources of error; this is particularly true where one hopes to measure a strain of 10^{-21}/\sqrt{\text{Hz}} from 10^{-3} to 10^{-1} Hz. We have compiled a list of a number of spurious forces, shown in Table 1, which could disturb the test masses at the level of about 10^{-19} \text{g}/\sqrt{\text{Hz}} or which could give an erroneous length measurement of 10^{-11}
Such a list is, needless to say, quite long. What follows are brief comments on those effects which we believe are the dominant ones, organized according to whether the effect accelerates the test mass or contributes an error to the length measurement.

Forces on the Test Masses

Accelerations due to Solar Cosmic Rays
Residual Gas Pressure
Gravity Gradient Noise from Spacecraft
Gravitational Force Changes from Fuel Usage
Spacecraft Distortions from Solar Fluctuations
Radiation Pressure from Changing Thermal Gradients
Galactic Cosmic Rays
Electrostatic Charge on Test Masses
Diamagnetism of the Test Masses
Non-uniform Outgassing
Radiometer Effect
Microparticle Impacts
Gamma Rays Impacts

Measurement Errors
Telescope Thermal Expansion
Laser phase noise
Irregularities in Optical Surfaces
Laser Beam Pointing Variations
Index Changes from Electron Density Fluctuations
Dust Dispersion
Timing Errors in Phase Detection System

Thermal Variations in Beamsplitters

Table 1. Possible Sources of Error. The sources are listed in approximately decreasing magnitude. See the discussion in the text.

Forces on the Test Masses

The biggest disturbance known to affect the test masses is the momentum
transfer from large outbursts of solar cosmic rays. Their contribution is normally negligible, but a major solar outburst would overwhelm the interferometer. Fortunately, these events are rare and their timing is known from other data.

Our present estimates of the limitations from other noise sources in each part of the spectrum are given in Figure 2. The shot noise in the detected laser signals dominates above $10^{-3}$ Hz. From $1 \times 10^{-5}$ to $1.5 \times 10^{-3}$ Hz, the noise level shown is due to several effects. One is random impacts from residual gas molecules in the cavity for an assumed pressure of roughly $10^{-11}$ torr. Other noise sources in this frequency range are time-varying gravity gradients due to temperature fluctuations of the outer layers of the spacecraft in response to fluctuations in the solar heating, and changes in the mass distribution of the fuel for counteracting the radiation pressure and solar wind forces on the spacecraft. Careful attention to these effects is needed in order to prevent them from considerably increasing the error budget.

![Graph showing spectral density of noise sources](image)

Figure 2. The spectral density of the expected noise sources in each part of the spectrum. The sensitivity declines between .1 and 1 Hz because the wavelength of the gravitational wave becomes shorter than the interferometer arm.
Galactic cosmic rays also can be a white noise acceleration source. The momentum transfer resulting from high energy cosmic rays (>100 MeV) is appreciable, but is one to two orders of magnitude below that from the residual gas pressure. Lower energy cosmic rays do not penetrate the spacecraft and drag-free cavity wall.

An electrostatic charge will build up on the test mass from cosmic rays impacts, and interact with any stray electric field in the cavity. We intend to monitor the potential fluctuations of the test mass, to restrict them to less than a 3 μV/√Hz and to keep the stray field across the cavity less than 1 V/m.

Below roughly 10⁻⁵ Hz, it appears very difficult to avoid serious limitations due to the changing temperature inside the spacecraft. In this spectral region, the curve shown in Figure 2 is based on temperature gradient fluctuations inside the cavity containing the test mass, which cause unequal thermal radiation pressure forces on opposite sides of the test mass. A three-stage thermal isolation system was assumed, so the slope of the resulting noise versus frequency curve is very steep.

**Measurement Errors**

The largest sources of measurement error can be controlled or measured. Thermal expansion of a telescope contributes a length change to one arm of the interferometer which is about the level of interest, but could be monitored if necessary. Laser phase noise will be reduced by locking the solid-state lasers to a reference cavity. Slight motion of the beam across irregularities in the optical surfaces could change the path length, and will be minimized. Mis-pointing of a telescope would change the phase arrival time. However, pointing to within 1 milliarcsecond is feasible and appears sufficient to control this source of error. Index changes in the interplanetary medium caused by electron density fluctuations can be monitored by a microwave link between satellites.

**Summary**

We continue to refine the design of a space-based interferometric antenna for gravitational waves and to analyze the sources of noise. We currently expect that a shot-noise limited strain sensitivity of 1 x 10⁻²¹/√Hz could be achieved over the frequency range 10⁻³ to 10⁻¹ Hz, with a decreasing, but still useful, sensitivity to 10⁻⁶ Hz. This should make possible the detection of periodic gravitational...
radiation from binary star systems and the search for pulses which might have been emitted near the epoch of galaxy formation.

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References
