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# GRAVITATIONAL RADIATION OBSERVATIONS ON THE MOON

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## ABSTRACT

A Laser-Interferometer Gravitational-Wave Observatory (LIGO) is planned for operation in the United States, with two antennas separated by several thousand kilometers. Each antenna would incorporate laser interferometers with 4 km arm lengths, operating in vacuum. The frequency range covered initially would be from a few tens of Hz to a few kHz, with possible extension to lower frequencies later. Similar systems are likely to be constructed in Europe, and there is a possibility of at least one system in Asia or Australia. It will be possible to determine the direction to a gravitational wave source by measuring the difference in the arrival times at the various antennas for burst signals or the phase difference for short duration nearly periodic signals. The addition of an antenna on the Moon, operating in support of the Earth-based antennas, would improve the angular resolution for burst signals by about a factor 50 in the plane containing the source, the Moon, and the Earth. This would be of major importance in studies of gravitational wave sources. There is also a possibility of somewhat lower noise at frequencies near 1 Hz for a lunar gravitational wave antenna, because of lower gravity gradient noise and microseismic noise on the Moon. However, for frequencies near 0.1 Hz and below, a $10^7$ km laser gravitational wave antenna in solar orbit would be much more sensitive.

## INTRODUCTION

Major benefits to gravitational wave astronomy are possible from the addition of a low-mass laser gravitational wave antenna on the Moon to an Earth-based antenna network. The general field of gravitational wave astronomy, plans for terrestrial laser antennas, and progress so far have been reviewed recently by Thorne,[1] Hough[2] and others.[3-6] If present efforts proceed in a timely fashion, the prospects appear good for initial operation of about four antennas with 3 or 4 km arm lengths within the next 5 or 6 years. Rapid further improvements in sensitivity are likely over the following few years as better laser systems, more efficient optical recycling methods, and other improvements are implemented. Thus we expect that many gravitational wave signals will have been observed by multiple antennas on the Earth soon after the year 2000.

Two types of gravitational wave sources[1] which are likely to be observed are the coalescence of neutron star binaries and supernova explosions. However, other types of sources also may well be found. One of these is the coalescence of black hole-neutron star and black

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hole-black hole binaries, which could be distinguished easily from neutron star binary coalescence by the rate of change of the observed frequency and the final frequency. Information on the number of such objects would help in understanding star formation and evolution processes. Also, surface distortion waves in neutron stars induced by accretion disk material during the spin-up process may be observed.

For all of the above types of sources, improved information on the location of the sources would be of major importance. The directional information obtainable from a number of antennas at different locations on the Earth has been investigated in detail by Gürsel and Tinto.[7] For moderate signal-to-noise ratios, an angular resolution of a degree or better will be achieved at a frequency of a few hundred Hz. However, adding an antenna on the Moon can give roughly a factor 50 better angular resolution in the plane containing the source, the Earth, and the Moon for bursts or short duration periodic signals. For signals which recur several times over a period of a week or more and are away from the ecliptic, the accuracy of both coordinates can be improved. The additional accuracy in angular positions which can be obtained with a lunar antenna thus appears to be of high value in studies of gravitational wave sources.

The development of gravitational wave antennas based on laser interferometers has advanced to the point where prototypes are in operation, detailed engineering of full-scale ground-based instruments has begun, and an initial conceptual design of a space-based instrument has been made. The method of operation of such antennas will be described briefly in the next section. This will be followed by a review of the seismic noise background on the lunar surface and a description of design parameters for a possible lunar gravitational wave antenna. Finally, the expected sensitivity will be discussed, and conclusions given concerning the development of a lunar antenna.

The general conclusions in this paper are similar to those in an earlier paper by Stebbins and Bender.[8] However, considerable new material has been added and different estimates of some of the lunar antenna parameters are used. Some corrections also have been made.

## GRAVITATIONAL WAVE OBSERVATORIES

Gravitational wave interferometers[1] detect the very faint strain induced by a passing wave through the interferometric comparison of the lengths of two arms oriented at right angles (Fig. 1). The ends of the arms are defined by test masses, inertially suspended, carrying the interferometer optics. A gravitational wave, impinging from above, causes the arms to expand and contract out of phase, thereby producing a shifting fringe pattern. The crux of the matter is the elimination or reduction of all other causes of apparent differential length change. Since the gravitational wave strain amplitude may be only as large as, say, a few times $10^{-21}$ at 1 kHz for the coalescence of a neutron star binary 10 Mpc away, the experimentalist needs to be concerned with spurious accelerations like seismic or thermal noise, and measurement noise, such as shot noise.

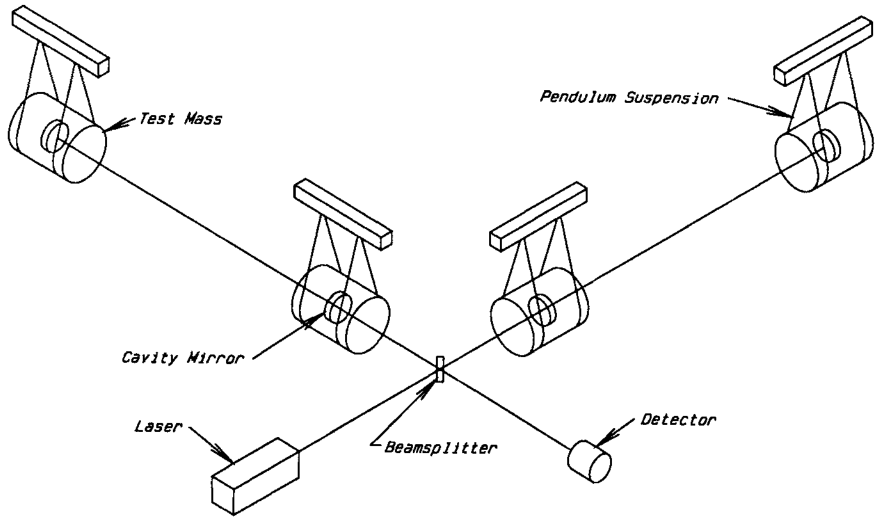


Fig. 1. A schematic representation of a gravitational wave interferometer. Laser light is fed to two Fabry-Perot cavities by a single beamsplitter. A gravitational wave traveling perpendicular to the plane of the detector will cause the arm lengths to change out of phase. Its passage is detected by a time varying fringe pattern.

The noise budget for terrestrial and lunar interferometers is dominated by the photon shot noise, the thermal noise in the suspension of the test masses, ground motion (i.e. seismic noise), the gravity gradient noise (the spurious acceleration of the test masses induced by gravitational coupling to moving masses nearby), fluctuating radiation pressure force on the test masses, and the uncertainty principle limitation. It is important to note that the last three of these noise sources are associated with the endpoints of the interferometer, whereas the response is dependent on the length of the interferometer. The photon shot noise is proportional to the square root of the length for a broadband light recycling interferometer. Overall, the signal-to-noise ratio increases with the length of the interferometer, until the light storage time becomes comparable with the gravitational wave period.

The proposed spaceborne interferometer[9,10] is different from the terrestrial and lunar versions in that the test masses bearing the optics are in nearly drag-free chambers within three different spacecraft. The three spacecraft are put into solar orbits with one year period so that they maintain a relatively constant separation. The current proposal[11] is to have the cluster of spacecraft located near the L-5 point of the Earth-sun system, with separations of about $10^7$ km.

## LUNAR SEISMIC NOISE BACKGROUND

The seismicity of the Moon has been measured by geophysical experiments placed on the lunar surface by the four Apollo landers. The results are summarized by Lammlein,[12] with important additional information in Goins et al.[13] The Apollo data are dominated by discrete seismic events lasting 30 minutes to 2 hours because of trapping of the waves in a shallow layer near the surface. There were about 1000 events per year. The rate of events varied at the four Apollo stations by nearly a factor of 5. The Apollo 12 site was quietest, probably because of its shallow regolith (2-4 m).

The lunar seismic events can be divided into four classes: (1) Small moonquakes, occurring at great depths, are triggered by tidal forces. Ninety percent of all deep seismic events had characteristic traces which identified their foci of origin. Most of the remainder were too weak to be traced. (2) Large moonquakes occur near the surface, but happen only a few times per year. (3) Meteoroids impact on the surface. These rare events can be one hundred times larger than the average deep moonquake and can last up to 4-5 hours. (4) Small high frequency signals are attributed to thermoelastic stresses in equipment left at the site, small meteoroid impacts within 10 km and micromoonquakes close to the seismograph stations. The micromoonquakes began two days after sunrise and decrease rapidly after sunset. They are thought to originate with thermally induced cracking or movement of rocks or with soil motion on slopes.

The deep moonquakes, the surface moonquakes, and the meteroid impacts all have signatures which allow them to be identified by seismometers at the site and vetoed out of the gravitational wave data. Even the weaker moonquakes could be traced with more sensitive seismographs, so long as they are separated in time. But, if we extrapolate the results from Fig. 30 in Ref. 12, the smallest moonquake signals become so numerous that they constitute a seismic background at an rms displacement spectral density of $1 \times 10^{-11}$ m/$\sqrt{\text{Hz}}$. However, it should be remembered that the extrapolation to lower amplitude disturbances could either overestimate or underestimate the actual background level.

The spectrum of the observed moonquake signals is essentially flat from the bottom of the bandwidth of the Apollo long-period instruments at 0.25 to 1 Hz. By contrast, the terrestrial background at moderately quiet sites is about 100 times greater in amplitude at 1 Hz and rises rapidly toward the low end of the Apollo band. The lunar seismic level for deep moonquakes decreases roughly as the inverse square of the frequency at higher frequencies, as it does for the Earth. However, the less frequent shallow moonquakes have substantial amplitudes up to at least 10 Hz.

In deciding how much seismic attenuation is needed for a lunar gravitational wave antenna, the question to be answered is what frequency of interruptions in acquiring data is acceptable. From Fig. 30 in Ref. 12, it appears that disturbances will exceed $1 \times 10^{-10}$ m/Hz$^{0.5}$ roughly once a day and $1 \times 10^{-9}$ m/Hz$^{0.5}$ once a month because of meteroid impacts or large shallow moonquakes. Since events last roughly 30 min to 2 hours, but a shorter time at close to maximum amplitude, a design disturbance level somewhere in the range

$1 \times 10^{-10}$ to $1 \times 10^{-9}$ m/Hz$^{0.5}$ for up to 10 Hz would be reasonable. We will use the higher level in this paper.

## LUNAR GRAVITATIONAL WAVE ANTENNA

An important consideration for a laser gravitational wave antenna to go on the Moon at an early date is to keep the mass as low as possible. For this reason, some of our design parameters for a lunar antenna are substantially different from those for ground-based antennas. However, a number of our choices are similar to those of the Caltech-MIT Project for the Laser-Interferometer Gravitational Wave Observatory (LIGO), which has looked at advanced designs for terrestrial instruments.

Another significant requirement is to minimize the amount of travel time necessary outside the lunar base to set up the antenna and to maintain it. For this reason, we assume an interferometer arm length of 5 km. However, when vehicles suitable for travel over large distances become available, baselines 10 times this long could be considered. In this case, a site with elevations for the end points 200 meters higher than the terrain in between would be required.

In the absence of a lunar atmosphere, no buried vacuum pipe between the end mirrors is needed, eliminating the costliest part of a terrestrial interferometer. However, because of the 300 K range in the surface temperature, thermal stability will be a major factor in the instrument design. The end stations will be insulated from incident sunlight, probably using a combination of locally derived materials and insulating blankets, and the ends of the ground paths beneath the laser beams may need to be shaded. The optical layout probably would follow that of the initial LIGO design, with the two Fabry-Perot cavities fed from a common beamsplitter, and with light recycling. The end mirrors would have a reflectivity suitable for containing up to $10^4$ bounces in each arm, or a 20 msec storage time.

At frequencies above roughly 30 Hz, the main noise source for both the lunar and terrestrial antennas will be photon shot noise. The light recycling is taken to be adjusted for optimum sensitivity at 300 Hz. As an example, the light level assumed by Thorne[1] for an advanced terrestrial detector is 100 W of detected power. We assume about 10 W for the lunar antenna, mainly because of time lags for implementing new developments on the Moon and more concern about the lifetimes of the lasers and of critical optical elements. The noise level would then be a factor 3 worse than for a terrestrial antenna in this frequency range.

The most important noise source for a lunar antenna at frequencies up to about 30 Hz is likely to be thermal noise in the final pendulum supports for the mirror masses. Inelastic dissipation in the flexing wire of the pendulum supporting the test masses causes kT noise. The rms displacement amplitude spectral density of the thermal noise for an oscillator with velocity damping is given by[4]:

$$(4kT\omega_o/mQ\omega^4)^{0.5}, \quad \omega \gg \omega_o$$

where k is the Boltzmann constant, T is the temperature, $\omega_o$ is the natural resonant frequency of the suspension, m is the mass, Q is the quality factor of the material, and $\omega$ is the working frequency. Although much larger masses will be used in terrestrial antennas, we assume a mass of 30 kg for each Fabry-Perot cavity mirror. The pendulum frequency is taken to be 0.3 Hz, corresponding to a pendulum length of 0.4 meters.

Definite information on the maximum achievable Q for different types of wires which might be used in the final pendulums is not yet available. Early measurements[14] gave a lower bound of $10^7$ for a pendulum mass of less than a kg and 1 sec period. However, it appears likely that considerably higher products of m and Q will be achievable with careful design and with the optimum choice of wire material. We will use a value of $1 \times 10^9$ for a 30 kg load, subject to verification by laboratory experiments which could be done in the next few years, and assume here that the temperature is 300 K. The thermal noise level is then $2.6 \times 10^{-17}$ $(1\ \mathrm{Hz/f})^2$ $\mathrm{m/Hz}^{0.5}$ above 0.3 Hz.

As in the LIGO design, there will be a secondary interferometer servoing the support points of the final mirror suspensions together so that both arms experience the same seismic input to a high degree. To the extent that the main suspensions' response can be made identical, the seismic input will not disturb the measurements since it will be common-mode in both arms. This should provide an additional isolation factor of perhaps 0.001.

Even with the use of the support point interferometer and servo system, plus the low seismic noise level on the Moon, further seismic isolation must be provided. The reason is to reduce the common mode motion of the support points to acceptable levels. In practice, this must be done for all 6 degrees of freedom of the support point motions in order to avoid the effects of cross-coupling between modes.

The first stage of isolation for the support points can be passive. However, the amount of passive isolation will be limited by weight constraints, so active isolation also will be important. To keep the antenna as compact and as light as possible, we assume two-stage active isolation systems would be used for each support point, with open-loop frequencies of about 1 Hz for the individual sensors and closed-loop frequencies of 0.03 Hz for the system.

The thermal noise in the sensors also must be considered. Since tilts, vertical motion, and rotation about the vertical must be sensed, as well as horizontal displacements, the thermal noise levels in a number of the sensors will be much higher than for simple pendulums. We will take the thermal noise level of $2 \times 10^{-14}$ $(1\ \mathrm{Hz/f})^2$ $\mathrm{m/Hz}^{0.5}$ above 1 Hz and $2 \times 10^{-14}$ $\mathrm{m/Hz}^{0.5}$ at lower frequencies for the common-mode displacement of support points for the interferometers, which corresponds roughly to Q's of about $10^5$ for the sensors. Isolation systems of this kind, but with closed loop frequencies of about 0.1 Hz, have been suggested for use in separate 1-30 Hz antennas for terrestrial gravitational wave observatories.[15]

The main parameters for the lunar gravitational wave antenna are summarized in Table I. Based on the type of antenna discussed above, the photon shot noise, the seismic background noise, and the thermal noise for the final pendulum suspensions are shown in Fig. 2, along with estimates for two other noise sources.

Cosmic rays will impart spurious accelerations to the test masses of a lunar interferometer. For a mass density of 100 $\mathrm{kg/m}^2$

Table I. Parameters of a lunar antenna used in the evaluation of the noise budget.

| Antenna Parameters |
|---|
| Length - 5 km |
| Thermally Insulated End Stations |
| Fabry-Perot Optics with Light Recycling |
| Temperature - 300° K |
| Suspended Mass - 30 kg |
| Main Suspension: |
| Resonant Frequency - 0.3 Hz |
| Q - $1 \times 10^9$ |
| Support Servo Isolation Factor - 0.001 |
| Support Point Isolation Systems: |
| Two Stages |
| Six Axes |
| Resonant Frequencies - 0.03 Hz |
| Thermal Noise - $2 \times 10^{-14}$ $(1\ Hz/f)^2$ $m/Hz^{0.5}$, f > 1 Hz |

surrounding the test masses, the cutoff for cosmic ray penetration is about 100 MeV. Higher energy cosmic ray protons will typically deposit roughly this amount of energy in the test masses. The resulting white noise acceleration due to the galactic cosmic rays will produce the noise level shown in Fig. 2. This source of noise, not found in terrestrial antennas, does not pose a significant problem. Major solar flares can cause much higher disturbance levels, but would not cause loss of data more than a few days per year.

The gravitational coupling of local mass motions to the test masses is called gravity gradient noise. Seismic waves, trapped in a thin surface layer, may be the main source of this irreducible noise. However, a rough estimate of the effect indicates that it is small (Fig. 2). Note that the gravitational wave interferometer

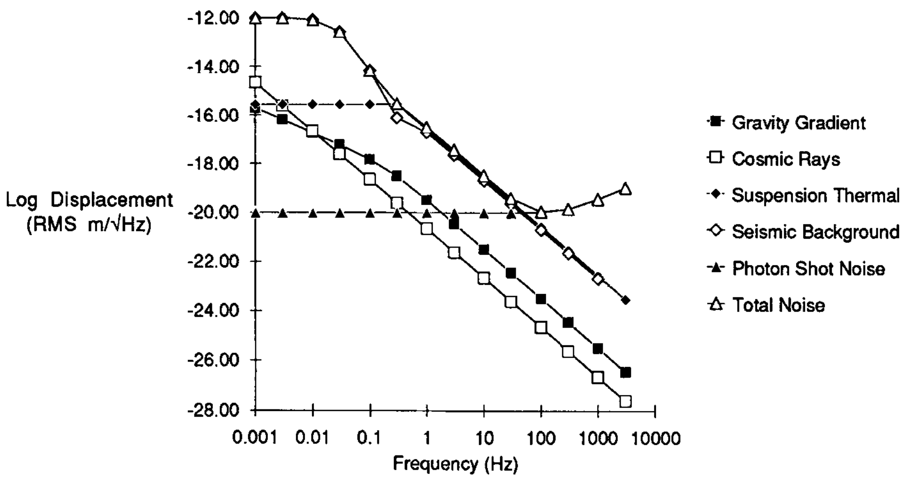


Fig. 2. Noise sources for a lunar gravitational wave interferometer.

would have to be remote enough from the lunar base so that the activities there would not disturb the antenna, whether by gravity gradient noise or by seismic noise.

## ANTENNA SENSITIVITIES

The estimated sensitivities for observing gravitational waves of spectral amplitude h (in units of $Hz^{-0.5}$) of the different types of antennas are shown in Fig. 3 for frequencies up to 3 kHz. A factor allowing for averaging over source directions and polarization[1] has been included. Also, below the resonance frequency of the final pendulum support for the mirrors, the loss in sensitivity of the antenna is allowed for. It is assumed that active damping is used to minimize the extra antenna noise at resonance.

The curve for the terrestrial antenna is based on the assumption that the seismic isolation can be made sufficient so that other noise sources dominate. The gravity gradient noise level is taken from Saulson.[16] The thermal noise level for the final pendulum suspensions is taken to be a factor 3 lower than for the lunar antenna. This is mainly because of the much heavier mirror mass which can be used. The resulting curve for the terrestrial antenna is dominated by the gravity gradient noise below 3 Hz, the thermal noise in the final pendulum suspensions from 3 to 30 Hz, and photon shot noise at higher frequencies. However, it should be remembered that better performance at frequencies other than 300 Hz could be achieved for both lunar and terrestrial antennas by different choices of the storage time.

The lunar antenna curve is lower than the other two only over a narrow frequency range near 1 Hz. However, the sensitivity of the lunar antenna is close to that of the terrestrial antennas over almost all of the frequency range. If a 50 km baseline antenna on the Moon becomes possible at some future time, the lunar antenna

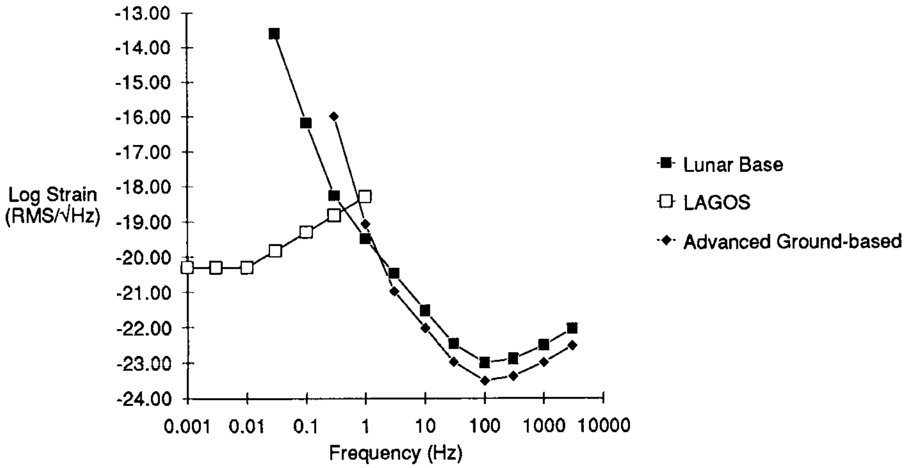


Fig. 3. Comparative sensitivities for three types of gravitational wave interferometers. The lunar base instrument improves the angular resolution of a terrestrial network by a factor of 50.

sensitivity might exceed that of the terrestrial antennas. The curve for the Laser Gravitational Wave Observatory in Space (LAGOS) is much lower than the other curves at 0.1 Hz and lower frequencies.

## CONCLUSIONS

Achieving the sensitivity shown in Fig. 3 for a lunar gravitational wave antenna will require technology development efforts in several areas. First, a careful study needs to be made of the overall mass requirements for a lunar gravitational wave antenna. Questions such as how to clamp the mirror masses and other suspended elements for transport, how to provide the initial optical alignment, and what kind of enclosures the optical elements should be mounted in need to be investigated. The optical apparatus might be pictured, for example, as mounted in three to six units, with separate electronics packages. The optical units would be connected together as necessary and covered with insulating material, as required, with care taken to avoid dust problems. Tentative design approaches such as this need to be investigated in order to start the process of obtaining estimates of the overall mass and power requirements.

A second important area is the development of suitable space-qualified stable lasers. Diode-pumped Nd-YAG lasers appear attractive for this purpose because of their high efficiency and long lifetimes. An output power equivalent to 10 W or more in the green is needed.

A third important area is the understanding of thermal noise generating mechanisms in materials for use in support wires for the mirrors. Work on such mechanisms probably will be carried out in connection with terrestrial antenna development, but the emphasis will be on considerably stiffer support wires because of the much larger mirror masses which can be used on the ground. The achievable Q is likely to be higher for thinner wires, and this makes up in part for the lower mass. However, the relationship between wire thickness and Q is not yet well understood. There also is a possibility that thermal noise levels may vary with frequency in a more favorable way than for the velocity damping model which usually is used.[18]

Finally, technology development is needed for the seismic isolation system for the final pendulum support points. Some work on such systems probably will be done in connection with both the broadband antennas and low-frequency antennas for use in terrestrial gravitational wave observatories. However, the resonance frequencies for terrestrial seismic isolation systems are likely to be considerably higher than for the lunar case, so at least different sensor designs are needed for the lunar isolation system. Also, reducing the isolation system mass is important for the lunar case.

Our main conclusion is that a low mass gravitational wave antenna could be designed and placed on the lunar surface at an early date. The operation of this antenna, in combination with the planned terrestrial network of antennas, would provide about a factor 50 improvement in angular resolution for pulsed or short duration periodic signals in the plane of the source, the Moon, and the Earth. This greatly improved resolution would be the major benefit to gravitational wave astronomy. Initial technology development studies for a lunar gravitational wave antenna thus are needed at an early date.

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