12. Lunar Surface Gravimeter Experiment

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The primary objective of the lunar surface gravimeter (LSG) is to use the Moon as an instrumented antenna (refs. 12-1 to 12-8) to detect gravitational waves predicted by Einstein's general relativity theory. A secondary objective is to measure tidal deformation of the Moon. Einstein's theory describes gravitation as propagating with the speed of light. Gravitational waves carry energy, momentum, and information concerning changes in the configuration of their source. In these respects, such waves are similar to electromagnetic waves; however, electromagnetic waves only interact with electric charges and electric currents. Gravitational waves are predicted to interact with all forms of energy.

The visible light, radio, and X-ray emissions, together with the cosmic rays, are the sources of all our present information about the universe. Gravitational radiation is a totally new channel that would be capable of giving information about the structure and evolution of the universe.

BASIC THEORY

It is possible to study many forms of energy-carrying waves by generating and detecting them in the laboratory. At present, this type of study is not feasible for gravitational radiation. The ratio of mass to electric charge for elementary particles is so small that only 1 graviton is emitted for every 10^{43} photons in ordinary laboratory experiments. Only objects the size of stars or galaxies can generate enough gravitational radiation to be detected by present apparatus.

Detailed mathematical analysis using Einstein's equations has shown that an elastic solid would serve as a gravitational radiation antenna. Dynamic forces associated with the gravitational waves set up internal vibrations in the antenna. These forces are somewhat similar to the gravitational forces that cause the tides. Observation of internal vibrations is limited by noise.

If gravitational waves of sufficiently high intensity covering certain bands of frequencies are incident on the Moon, internal vibrations of the Moon will be excited. These vibrations may cause oscillatory surface accelerations. Theory predicts that only the lowest allowed frequency and certain overtones can be excited in this way. The kinds of vibrations that are excited by gravitational waves are believed to have symmetry. Thus, the "breathing" mode of the Moon, in which all points of the lunar surface move outward together, and half a cycle later, all points move inward together, is not expected to be driven by gravitational radiation. However, the "football" mode is expected to be excited by gravitational radiation. In the "football" mode, all points on the lunar equator move outward at the same time that points on the lunar poles are moving inward. Half a cycle later, all points on the equator are moving inward while the polar regions are moving outward.

Very little is known about possible sources of gravitational radiation. An object may emit considerable gravitational radiation and have very little emission of light and vice versa. At present, the search for this radiation must be made by developing the best possible instruments and operating them at the limits of sensitivity. Approximate estimates suggest that present procedures have a fair chance of observing real effects by using the Moon because of the relative quiet of the lunar environment.

The Earth is also an instrumented antenna, but it has a high level of noise because of the atmosphere, the oceans, and seismic activity. Quiet periods exist when it may be possible to observe the coincident response of the Earth and Moon to gravitational waves. The surface acceleration of the Earth is measured with a somewhat similar gravimeter and recorded as a function of time. Comparisons between

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the lunar and terrestrial records should allow searches for simultaneous sudden surface accelerations. By delaying one recording relative to the other one, the rate of chance coincidences may be measured. A significant excess of zero-delayed as compared to time-delayed (chance) coincidences can establish the existence of correlations.

Experiments have been conducted in the kilohertz region using aluminum cylinder masses of several thousand kilograms that are isolated from terrestrial effects. The existence of such coincidences has been established using antennas at the University of Maryland and at the Argonne National Laboratory near Chicago, Illinois. The high frequency (seismic output) of the LSG will be compared with the records of the aluminum cylinder experiments in an effort to find numbers of coincident amplitude increases over and above the chance rate.

The LSG was also designed to measure the tidal effects on the Moon and to serve as a one-axis seismometer. The lunar orbit is slightly elliptical, and the Moon undergoes librations. For these reasons, the gravitational fields of the Earth and Sun sensed by a given part of the lunar surface will vary with time. This variation results in time-dependent tidal forces on the Moon. The figure of the Moon will be distorted in consequence of the tidal forces, and the amount of this distortion gives information about the internal composition of the Moon.

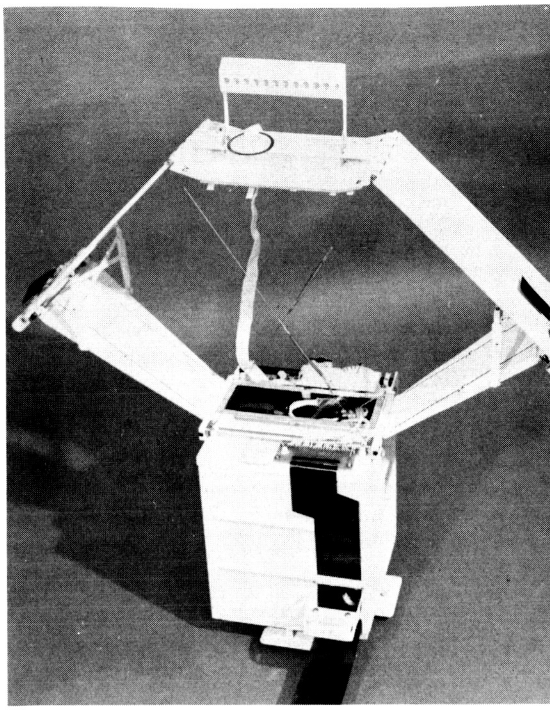

FIGURE 12-1.–Lunar surface gravimeter.

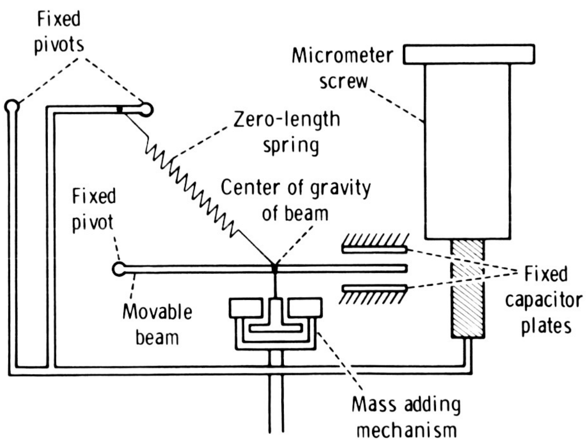

FIGURE 12-2.–Schematic diagram of the lunar gravity sensor.

EQUIPMENT

The LSG (fig. 12-1) was emplaced on the Moon by the Apollo 17 crew. This instrument is a sensitive balance with a mass, spring, and lever system and with electronics for observation of accelerations in the frequency range from 0 to 16 Hz. The LSG has a nominal sensitivity of approximately one part in 10^{11} of lunar gravity.

A schematic diagram of the spring-mass suspension system is shown in figure 12-2. In the instrument, the major fraction of the force supporting the sensor mass (beam) against the local gravitational field is provided by the zero-length spring. A zero-length spring is one in which the restoring force is directly proportional to the spring length; such a spring is very useful in obtaining a long-period sensor (ref. 12-9). Small changes in force tend to displace the beam up or down. This imbalance is adjusted to the null position by repositioning the spring pivot points by use of micrometer screws. The sensor mass is modified by the addition or removal of small weights, permitting the range of the sensor to be extended from Earth testing to lunar operation. The electronic sensing portion of the instrument consists of a set of capacitor plates. Two plates, which are part of a radio-frequency bridge circuit, are fixed to the frame of the sensor and are geometrically concentric with a third plate of similar size, which is attached to the movable beam of the sensor. The plates are so arranged that the center plate is located exactly between the two outer plates when the beam is exactly horizontal. If the force on the mass changes, it tends to move the beam, and the resulting bridge unbalance creates an ac error voltage. This voltage is amplified and rectified with the size of the output voltage determined by the direction of the displacement. A fixed dc bias voltage is applied to the capacitor plates balanced with respect to ground, and these plates are also connected to the rectified error voltage.

If the error voltage is zero, the balanced bias plate voltage produces equal and opposite electrostatic forces on the mass. If a positive error voltage is present, the voltage applied to one plate is increased and the voltage applied to the other plate is decreased. The resulting force tends to restore the mass to its originally centered position. This rectified voltage is a measure of the changes in surface acceleration. The mass does not follow fast changes. However, the fast-changing servomechanism error voltage is a measure of the rapidly changing components of the surface acceleration.

The LSG can also be operated with the voltage output not fed back to restore the beam to equilibrium. As indicated in figure 12-3, the different configurations have different responses to surface accelerations.

The data cover the frequency range from 0 to 16 Hz in three bands. The rectified integrated error voltage over the range dc to 1 cycle per 20 min gives information on the lunar tides. A filter with amplification covers the range from 1 cycle per 20 min to 3 cpm. Another filter amplifies the fast components in the range from 3 cpm to 16 Hz. The latter range is of interest for seismology and for search for high-frequency gravitational radiation from sources such as the pulsars. The complete response function of the sensor and electronics for several different configurations is given in figures 12-3 and 12-4.

THERMAL CONTROL

The gravimeter uses a metal spring with a force constant that is, in general, temperature dependent. There are two temperatures at which thermal effects are minimal; for the LSG, one of these occurs near 323 K. To obtain the required performance, it is necessary to control the temperature of the spring to within better than 1 mdeg near the optimum temperature throughout the lunar day/night cycle. Thermal control is accomplished by use of thermal insulation, which limits heat exchange with the lunar surface. A hole in the top of the LSG radiates heat to the cold sky so that an internal heater is required to maintain the 323 K temperature sensed by thermistors. A sunshade prevents the solar heat from directly entering the LSG. The sunshade is tilted at an angle corresponding to the latitude of the emplaced instruments. The thermal control system has controlled the temperature of the spring to within 1 mdeg.

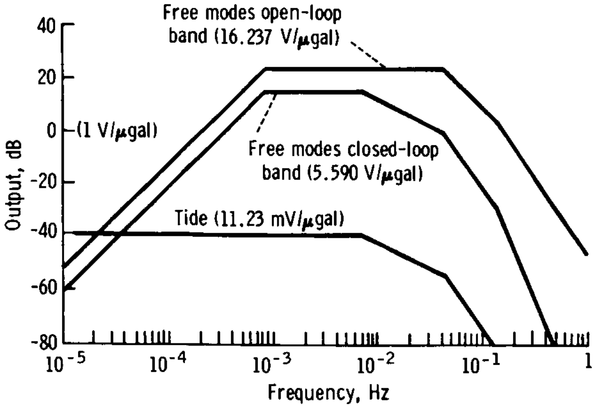

FIGURE 12-3.–Tide and free mode science channel frequency response.

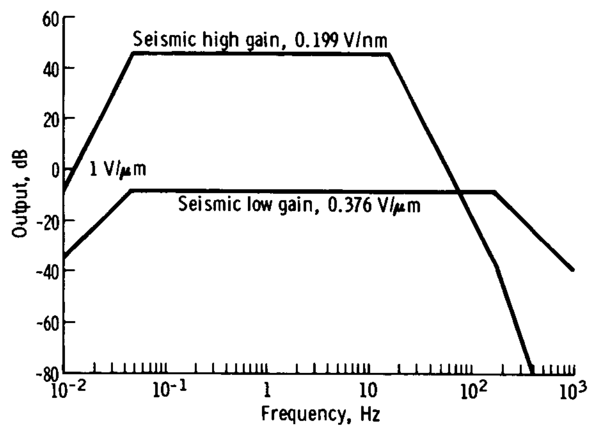

FIGURE 12-4.–Seismic science channel frequency response.

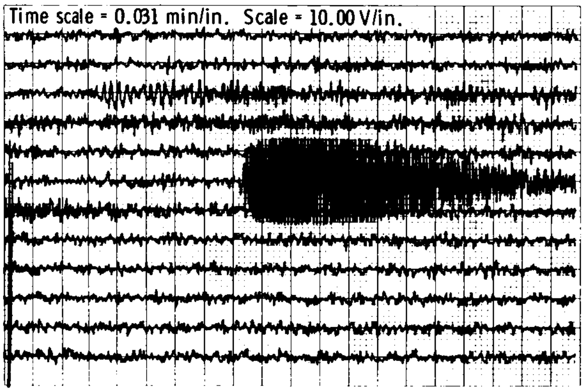

FIGURE 12-5.–Lunar surface activity near sunrise (April 1973).

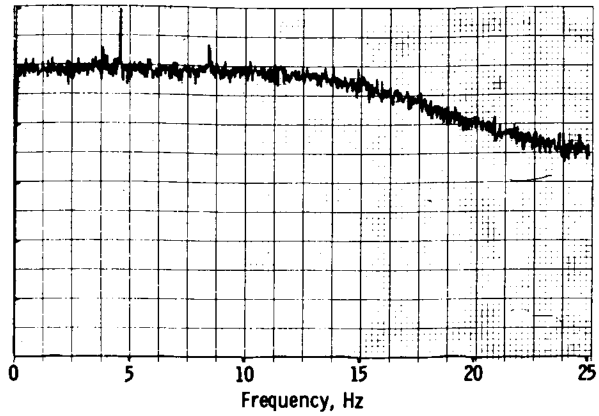

FIGURE 12-7.–Power spectrum analysis of quiet period.

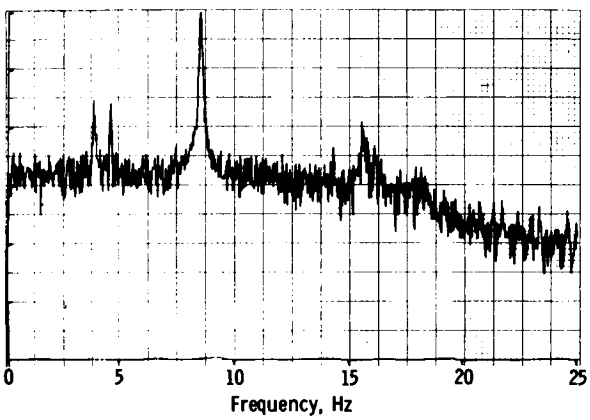

FIGURE 12-6.–Power spectrum analysis of lunar sunrise data.

When the LSG was emplaced, it was impossible to balance the beam by sending commands to add or subtract mass. The motion of the beam suggested that an additional force corresponding to lunar gravity acting on approximately a gram of mass would balance the beam. Such a force can be exerted by operating the mass-changing mechanism beyond the point of addition of all masses so that it contacts the beam, moving it to midposition. In this configuration, the instrument is apparently behaving like a gravimeter with resonances at 1.5 Hz and possibly at a much lower frequency. The seismic output appears to be that corresponding to the sensitivity indicated in figure 12-4, and noise output in the free modes open-loop band (fig. 12-3) suggests that surface accelerations are being sensed in these bands of frequencies. The seismic channel output during a several minute period associated with lunar sunrise is shown in figure 12-5. A power spectrum analysis of these data is depicted in figure 12-6. For comparison, the power spectrum of a period preceding sunrise is illustrated in figure 12-7. Thus, it appears that the LSG may carry out the search for gravitational waves.

ACKNOWLEDGMENTS

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