LUNAR SURFACE GRAVIMETER EXPERIMENT

FINAL REPORT

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

John J. Giganti, J.V. Larson, J.P. Richard
R.L. Tobias and J. Weber*+

CONTRACT NAS 9-5886

Department of Physics and Astronomy
University of Maryland
College Park, Maryland

January 1977

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

LUNAR SURFACE GRAVIMETER EXPERIMENT

FINAL REPORT

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

John J. Giganti, J.V. Larson, J.P. Richard
R.L. Tobias and J. Weber*+

CONTRACT NAS 9-5886

Department of Physics and Astronomy
University of Maryland
College Park, Maryland

January 1977

Supported in part by the Computer Science Center, University of Maryland, College Park

*also Department of Physics, University of California at Irvine
+Principal Investigator

DISTRIBUTION

1 copy to:	Mr. Christopher C. Kraft, Jr., Code BZ Director, NASA, Lyndon B. Johnson Space Center Houston, Texas 77058
1 copy to:	Mr. Tony C. Riggart, Code BC24 Contracting Officer Shuttle Payload Procurement Section NASA, Lyndon B. Johnson Space Center Houston, Texas 77058
1 copy to:	Mr. W. L. Eichelman, Code TN3 Technical Initiator NASA, Lyndon B. Johnson Space Center Houston, Texas 77058
4 copies to:	NASA Lyndon B. Johnson Space Center Technical Information Dissemination Branch Houston, Texas 77058 Attn: R. Shirley, JM6
1 copy to:	Dr. Alex Dragt, Professor and Chairman Department of Physics & Astronomy University of Maryland College Park, Maryland 20742
1 copy to:	Mr. John T. Wheeler, Code AT3 NASA, Lyndon B. Johnson Spacecraft Center Technology Utilization Officer Houston, Texas 77058
1 copy to:	Mr. Paul Roosen, Director Office of Contracts and Grants University of Maryland College Park, Md. 20742
1 copy to:	Dr. Joseph Weber, Professor Department of Physics & Astronomy University of Maryland College Park, Md. 20742
1 copy to:	Mr. John J. Giganti Department of Physics and Astronomy University of Maryland College Park, Md. 20742
1 copy to:	Dr. J.V. Larson 5526 Karen Elaine Dr. New Carrolton, Md.

Distribution (continued)

1 copy to:	Dr. J. P. Richard, Professor Department of Physics and Astronomy University of Maryland College Park, Md. 20742
1 copy to:	Mr. R.S. Tobias Research Assistant Department of Physics & Astronomy University of Maryland College Park, Md. 20742
1 copy to:	Mr. W.C. Nichols Department of Physics and Astronomy University of Maryland College Park, Md. 20742

LUNAR SURFACE GRAVIMETER EXPERIMENT

1. Introduction

The primary objective of the Lunar Surface Gravimeter (LSG) was to use the Moon as an instrumented antenna (refs. 1-8) to search for gravitational waves predicted by Einstein's general theory of relativity. A secondary objective was 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 is capable of giving information about the structure and evolution of the universe.

2. 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 one 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 had 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 quadrupole symmetry. Thus the "breathing" mode of the Moon, in which all points of the Lunar surface move together radially, is not expected to be driven by gravitational radiation. However, there exists a mode in which 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. This so-called "football" mode is expected to respond to gravitational radiation.

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. Experiments have been conducted in the kilohertz region using aluminum cylinder masses of several thousand kilograms that are very well isolated from terrestrial effects.

We have operated two "antennas" of this type -- one at the University of Maryland and the other at the Argonne National Laboratory near Chicago Illinois. If sufficiently large bursts of gravitational radiation are incident from outer space, these might cause coincident changes in output of widely separated antennas. Currently, it appears certain that coincidences occur, over and above the rate of accidentals (ref.9). It requires a very careful investigation to rule out all effects other than gravitational radiation, and such an investigation has not been completed. A major goal of the lunar surface gravimeter experiment is to search for correlations between the high frequency terrestrial experiments and changes in lunar surface acceleration.

The high frequency (seismic output) of the LSG then is 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.

Experiments have been proposed to detect high frequency gravitational radiation emitted by astronomical bodies known as pulsars by performing autocorrelations on data produced by seismometers on the earth (ref.10). The possibility exists for the analysis to be repeated using the seismic output of the LSG with improved sensitivity, because of the moon's lower level of noise.

3. Equipment

The LSG (fig. 1) was emplaced on the Moon by the Apollo 17 astronauts. 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^{10} of Lunar gravity.

A schematic diagram of the spring-mass suspension system is shown in figure 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 a spring in which the restoring force is directly proportional to the spring length; such a spring is very useful in producing a long-period sensor (ref. 11). Small changes in force tend to displace the beam up or down. This imbalance can be 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 and parallel to 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 imbalance creates an ac error voltage. This voltage is amplified and rectified with the size of the output voltage determined by the magnitude 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 zeroed, 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 fixed plate is increased, and to the other fixed plate it is decreased. The resulting force tends to restore the mass to its original centered position. The voltage required to balance the beam 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 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 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 17 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 3 and 4.

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 degrees K. To obtain the required performance, it is necessary to control the temperature of the spring to within better than 1 millidegree near the optimum temperature throughout the lunar day/night cycle. Thermal insulation 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 controlled heater is required to maintain the 323 degrees K. temperature sensed by thermistors. A sunshade prevents the solar heat from directly entering the apparatus. The sunshade is tilted at an angle corresponding to the latitude of the emplaced instruments. The thermal control system has successfully controlled the temperature of the spring to within 1 millidegree.

5. Chronology of the Experiment

The LSG experiment was deployed on December 12, 1972 by the Apollo 17 astronauts. The set-up procedure was to null the sensor beam by adding weights by means of a caging mechanism. However, even with both of the available masses added to the sensor beam assembly, it was not possible to balance it in the proper equilibrium position. The only time the beam moved was when the caging mechanism was in physical contact with it.

To determine if the movement of the beam was being obstructed, the Lunar Module Pilot rapped the exposed top plate on the gimbal; rocked the apparatus in several directions, releveled the instrument; and rechecked the tilt of the sunshade in an attempt to free the sensor beam. However, none of these actions produced any change in the operation of the instrument.

It was then determined that an error in arithmetic made by La Coste and Romberg, and known to the firm's highest officials, had not been corrected by La Coste and Romberg. This led to an instrument which had excellent performance in earth g and was just barely outside of the tolerances for variations of lunar site g. This error resulted in the mass of the counterweights being about two percent less than was necessary for operation in the Moon's 1/6-g gravitational field. Unfortunately, the procedure of adding the weights allowed only for up to plus or minus 1.5 percent for possible inaccuracies.

Therefore, it was necessary to balance the beam using a very small force applied by the mass adding mechanism. However, this changed the frequency response of the sensor to a significantly higher frequency than that originally intended. However, the balanced beam system had a much higher quality factor--about 25--instead of being critically damped. This led to much greater sensitivity than the intended design near the resonance and poor sensitivity at very low frequencies. The system was left in open loop (integrator shorted) mode.

After 45 days, no seismic signal was detected, and it was found that the sensor had deviated sufficiently from its proper equilibrium position to saturate the final amplifier. The beam was again centered, and the output observed during a terminator crossing (lunar sunrise or sunset), when rapidly changing temperatures would be expected to produce enough stresses on the Lunar surface to produce detectable seismic activity. Comparison with the Lunar Seismic Profile Experiment (LPSE) verified that the LSG was indeed detecting information from local seismic activity.

On April 19, 1973, the natural resonant frequency was successfully lowered to approximately 2.2. Hz., with a displacement sensitivity of 3.5 angstroms. The experiment was left in open loop to obtain some long term results before further experiments were attempted.

On September 26, the experiment was configured for the first time in closed loop operation, in order to detect tidal data. This also reduced the possibility of saturation, so the seismic gain was again returned to maximum. The spring constant and the beam assembly frequency response were measured.

In an attempt to further reduce the instrument's resonant frequency, another reconfiguration was performed on November 30 to better center the sensor beam with the mass caging mechanism. As a result, the natural frequency was lowered to approximately 1.5 Hz., and there was noticeable improvement in the free mode channel response. The tidal output was following its predicted pattern with an unexplained distortion in the high frequency region. Unfortunately, the tidal signal later began to show a constant reading at its minimum value, indicating a hardware failure in the tidal channel. No explanation could be found for the problem, and the experiment was left on December 7 in open loop mode with maximum seismic output.

The experiment continued to gather useful data until March 15, 1974, when the heating mechanism began to malfunction, making it impossible to accurately maintain a stabilized operating temperature without which no useful data could be obtained. However, the heating system regained normal operation on April 20.

Most of the data processing had been performed on the University of Maryland's Univac 1108 computer system. No large scale data reduction could be performed within the limits of the experiment's budget, because the 1108 computing costs were about $500 per days data. A digital Equipment Corporation PDP-11/40 computer system was acquired to decommutate the data from the source tapes, and for subsequent data analysis.

Financial support for the project came to an end on December 31, 1974. The University of Maryland continued a greatly reduced scale of data analysis using the PDP computer until its return was required by NASA on May 15, 1976. Efforts centered on performing the coincidence analysis between the LSG Data and the two aluminum cylinder detectors at Argonne and Maryland, and in analyzing free mode data to locate any periodicities in the signal output. The effort is continuing as resources permit with other computer facilities. Seismic data are currently being sent to investigators at the University of Texas at Galveston where studies are being conducted in conjunction with the Passive Seismic Experiments situated on other lunar sites .

6. Methods of Data Analysis

Data from the experiment were sent by telemetry from the ALSEP central station to one of several tracking stations on the Earth. Each tracking station would record the data from all of the ALSEP experiments onto an analogue range tape, which was then sent to a central processing center in Houston, Texas, where a digital tape was prepared containing sixteen thirty-six word logical records.

Each logical record provided in packed format thirty-one seismic channel voltage readings separated by .01887 seconds (except for the first reading in each record which was omitted to allow for synchronization information). Also included was one free modes channel reading, and one tidal (integrator output) reading, each representing a time average over .604 seconds. Data were transmitted giving the instrument temperature, and the reading of a clock located in the ALSEP central station which gave the elapsed time in milliseconds from January 1 of the current year. These data tapes were sent via air mail to the University of Maryland, where further data processing was to be done.

Considerable difficulty was at first experienced in reading the tapes on Maryland's Univac 1108 computer system, so it became necessary to check the data for proper time increment between records and stable experiment status, tide, and temperature readings.

Each data word was supplied in ten bit format, representing logarithmically the entire voltage range of each measurement. The seismic data were analyzed by filtering and Fourier analysis to detect significant movement of the sensor. The response curve to a typical narrow band filter used to separate the resonant frequency of the sensor from background noise is shown in Figure 7. Free modes data also were Fourier analyzed with the resultant power spectral density records being added together to improve the probability of detecting persistent periodicities in the free mode signal.

By early 1974 the new PDP 11 system was operating, and the quality of the packed data tapes had improved to a point that much of the error checking was no longer necessary. The seismic data were extracted and written on nine track tapes in 2048 sixteen bit word records each containing time information, and the free modes data were written onto disk for later processing. Additional programs were written to: a) read a record of seismic data, b) plot a power spectral density over the 2048 points, c) filter the data with any desired bandwith. Capabilities existed to scan several records of data for signs of seismic activity, "freeze" a particular record on the screen, determine the location and amplitude of the largest or any selected spectral peak, change the gain or filtering limits of the display, or to see a particular time series of data in slow motion.

7. Results

Figure 8 shows the sensor being excited by a single frequency of oscillation in the seismic band of operation. This event also produced a resonance at 8-9 Hz and a doublet resonant at 4 Hz as shown in the power spectral density plot for the free modes output as shown in figure 12. The excitation lasted for approximately half a minute.

Figure 9 shows the sensor being excited by two closely spaced frequencies in the seismic band, which produced a modulated interference pattern.

Figure 10 shows a lower frequency seismic resonance calculated to be around 1.6 Hz. A glitch resulting from a command being sent to the LSG from Earth occurred at 03:32:10. Figure 11 is on different time and amplitude scales, and shows the arrival times of compressional and shear modes of vibration.

Figure 13 shows the average of four power spectral density plots of free modes data. Figure 14 shows an averaging over thirty-six days of data. No statistically significant resonances are apparent in either band.

Direct comparisons of the LSG data with other seismic measuring devices on the Moon have shown it to have within a narrow bandwidth a greater degree of sensitivity. This would allow the LSG to become an effective window into the seismic activity of the Moon.

CONCLUSION

Our data analysis is not complete at this time because funding was terminated and our computer reclaimed by the United States Government. Analyses will continue with other resources until we have thoroughly studied the data for a ten day period when large numbers of coincidences were observed for the Maryland Argonne detectors.

The objective of employing the moon as a gravitational radiation detector has been met with a few Angstrom displacement sensitivity over the narrow band resonance near one hertz. A large number of lunar seismic events were observed and these data have been useful for the seismology investigations. Detailed analysis of the very low frequency data has revealed no evidence of excitation of the lunar free modes of oscillation.

REFERENCES

1. Weber, Joseph: The Detection of Gravitational Waves. Sci.Am., vol.224, no. 5, May 1971, pp. 22-29

2. Weber, Joseph: Pulses of Gravity. Science Year: The World Book Science Annual. Field Enterprises, Inc. (San Francisco), 1972

3. Weber, Joseph: Detection and Generation of Gravitational Waves. Phys. Rev., Vol. 117, no. 1, Jan. 1960, pp. 306-313.

4. Weber, Joseph: General Relativity and Gravitational Waves. Interscience Pub., Inc. (New York), 1961.

5. Weber, Joseph: Evidence for Discovery of Gravitational Radiation. Phys. Rev.Letters, vol. 22, no. 24, June 1962, pp. 1320-1324

6. Weber, Joseph: Gravitational Radiation Experiments. Phys. Rev. Letters, vol. 24, no. 6, Feb. 1970, pp. 276-279.

7. Weber, Joseph: Anisotropy and Polarization in the Gravitational-Radiation Experiments. Phys. Rev. Letters, vol. 25, no. 3, July 1970, pp. 180-184.

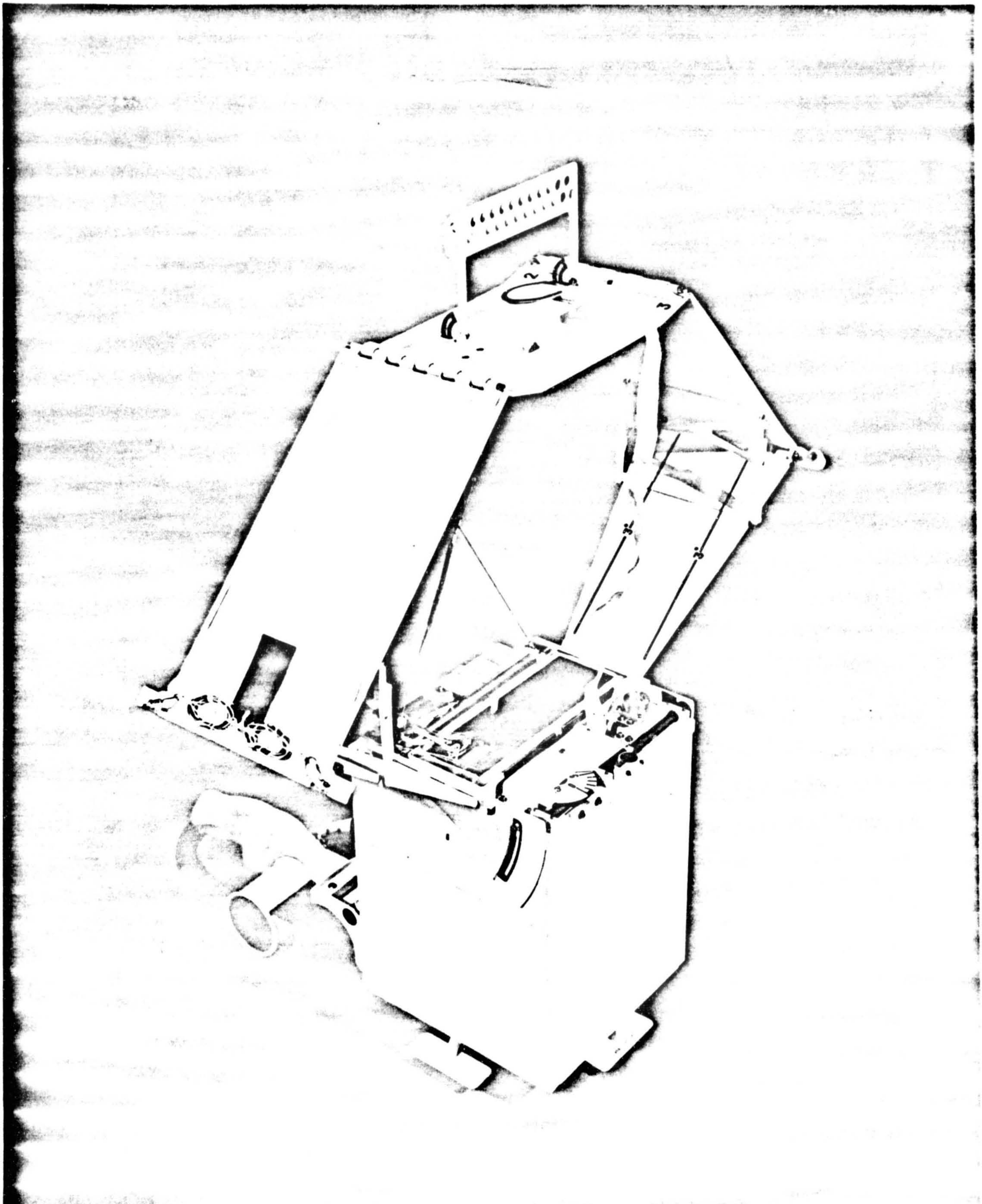
8. Weber, Joseph: Computer Analyses of Gravitational Radiation Detector Coincidences. Nature, vol. 240, no. 5375, Nov. 1972, pp. 28-30.

9. Lee, Gretz, Steppel, Weber: Phys. Rev. 14, 4, 893-906, 1976

10. F.J. Dyson, Astrophysical Journal 156, 529 (1969)

11. Flügge, Siegfried, ed.: Geophysik II. Vol. XLVIII of Handbuch der Physik, Springer-Verlag (Berlin), 1957, p. 803

Fig 1



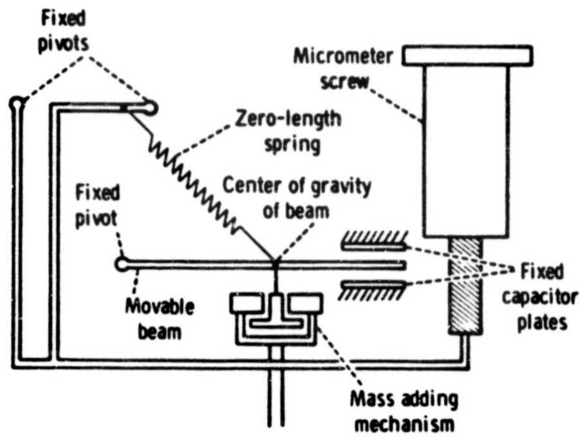


FIGURE 2.–Schematic diagram of the lunar gravity sensor.

Fig. 2

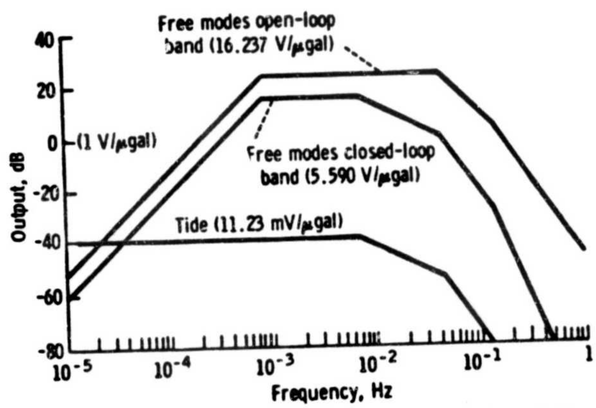


FIGURE 3.–Tide and free mode science channel frequency response.

Fig. 3

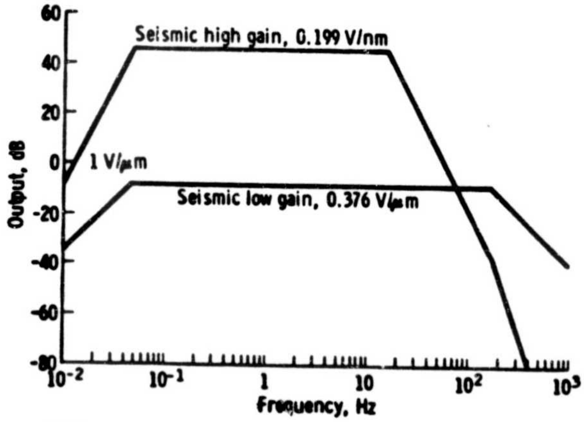
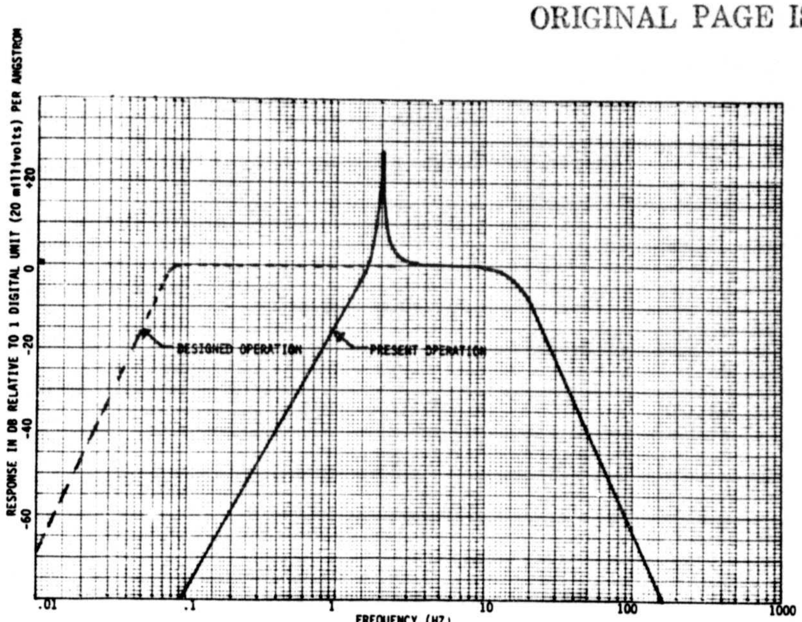


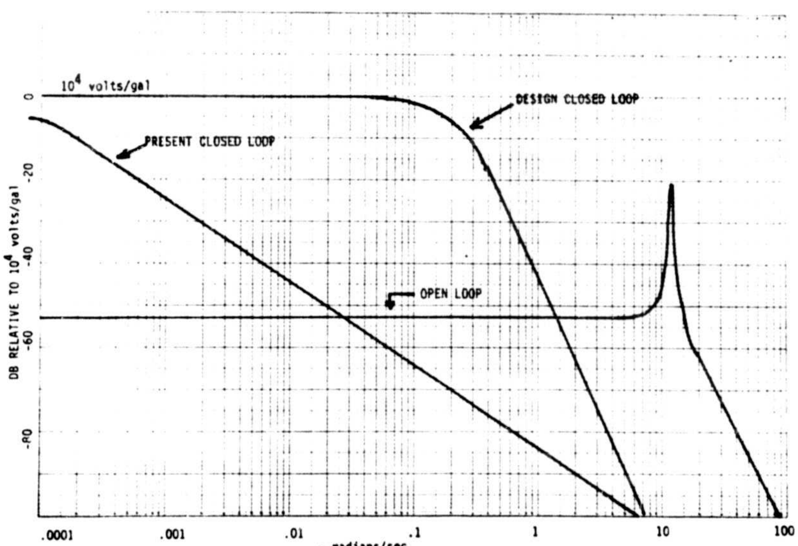
FIGURE 4.–Seismic science channel frequency response.

Fig. 4



SEISMIC RESPONSE CURVES IN THE HIGH GAIN SEISMIC MODE

Figure 5



MAGNITUDE RESPONSE CURVES FOR FREE MODES INPUT VOLTAGE/Δg in gals

Figure 6

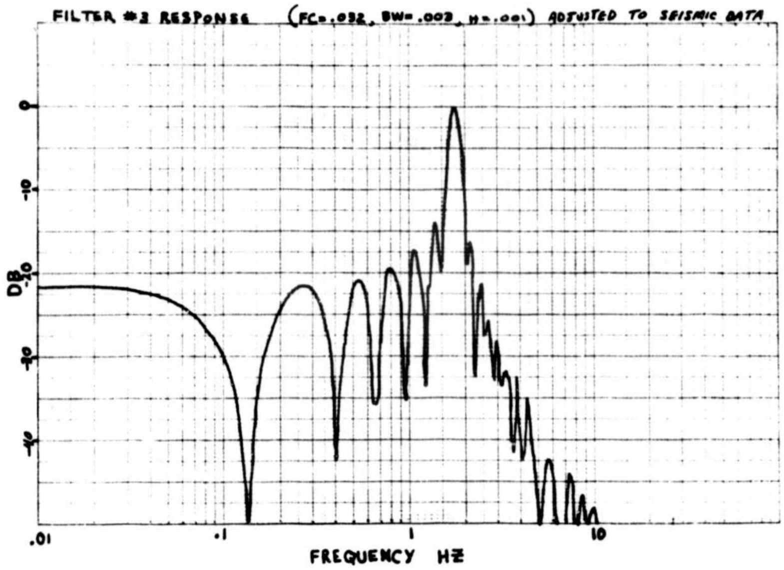
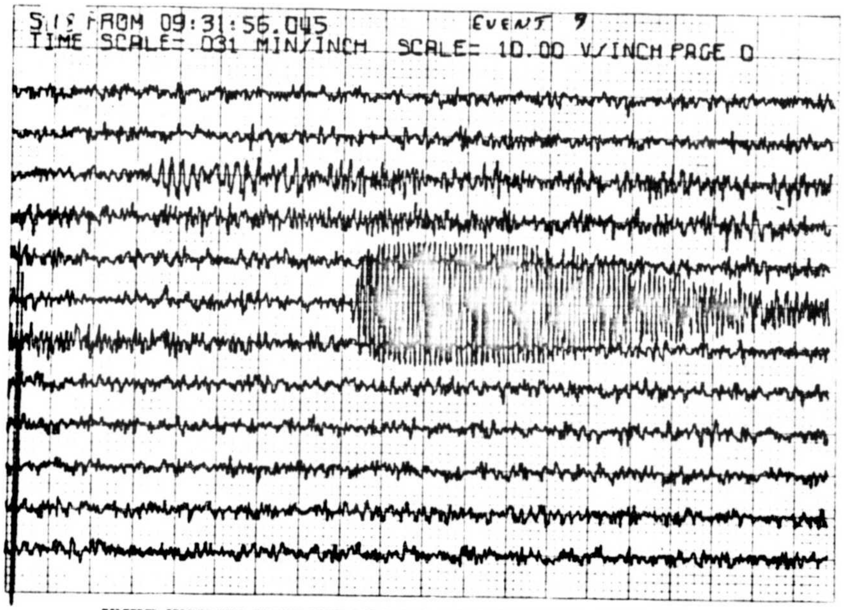
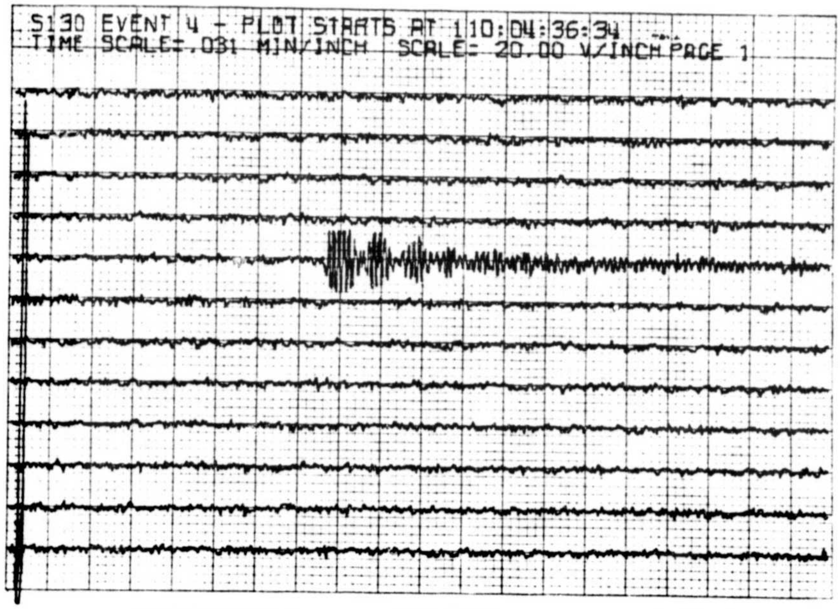


Figure 7



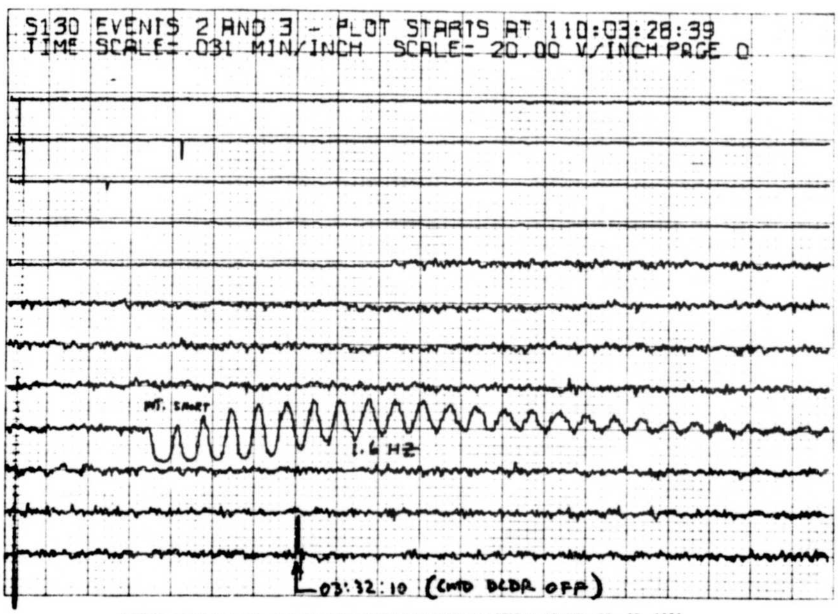
FILTERED SEISMIC DATA SHOWING EVENT OCCURING AT APPROXIMATELY 9:32 GMT APRIL 8, 1973

Figure 8



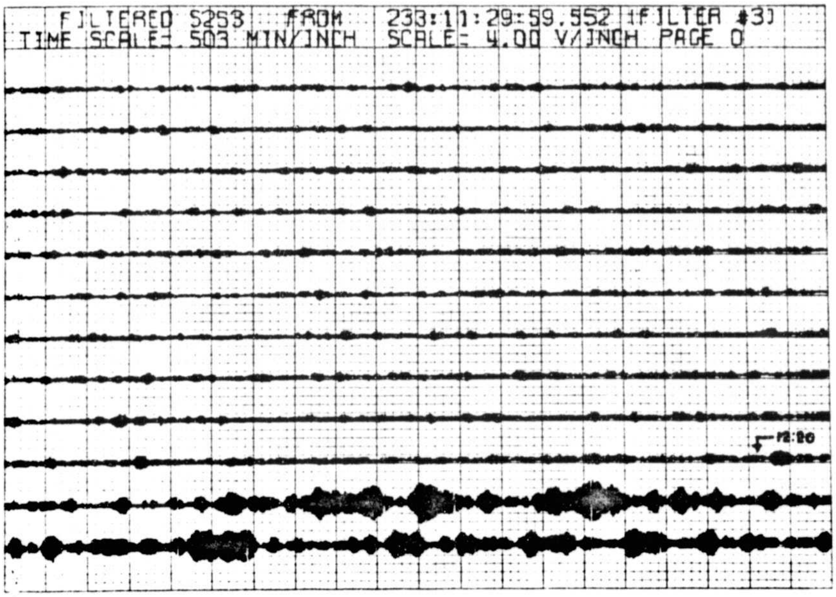
FILTERED SEISMIC DATA SHOWING EVENT OCCURING SHORTLY AFTER 4:36 GMT APR. 20, 1973

Figure 9



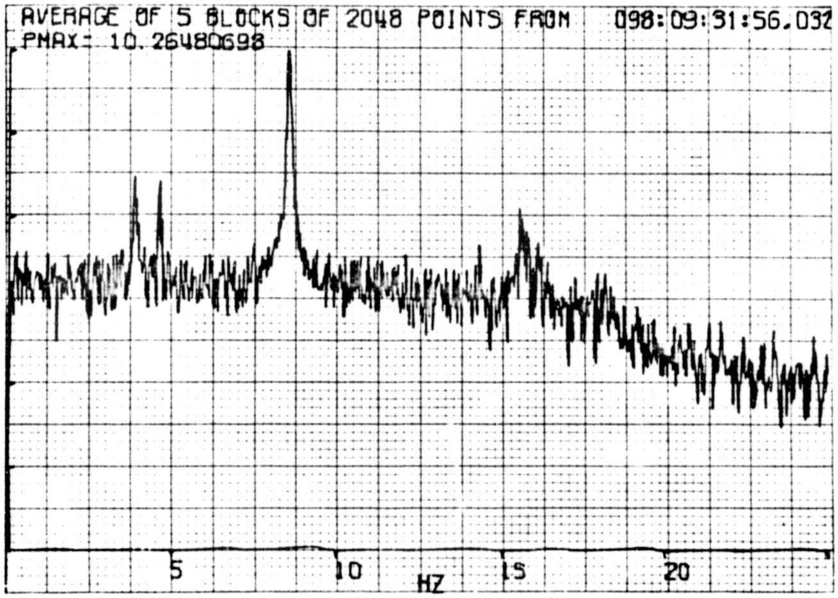
FILTERED SEISMIC DATA SHOWING EVENT OCCURING SHORTLY AFTER 3:28 GMT APR. 20, 1973

Figure 10



FILTERED SEISMIC DATA SHOWING EVENT SHORTLY AFTER 11:30 GMT SEPT. 21, 1973

Figure 11



POWER SPECTRAL DENSITY PLOT OF APRIL 8, 1973 DATA

Figure 12

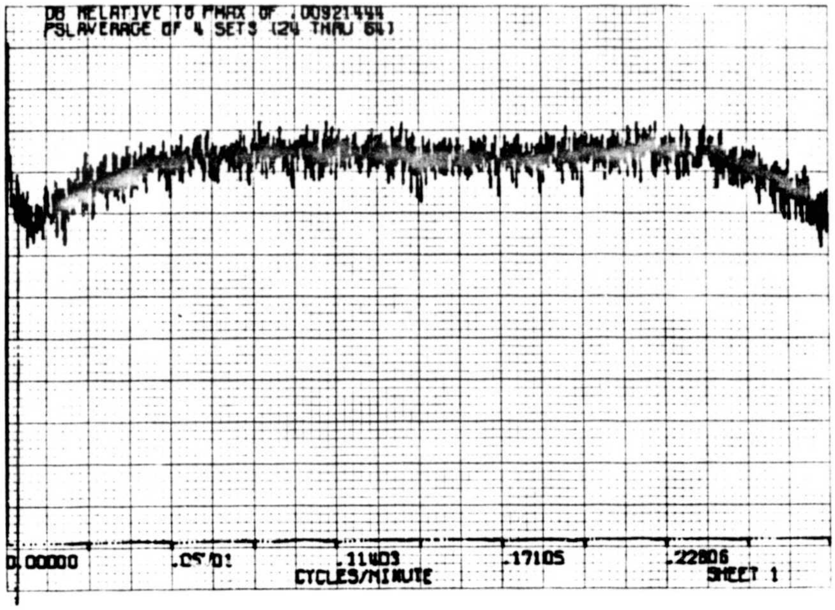


Figure 13

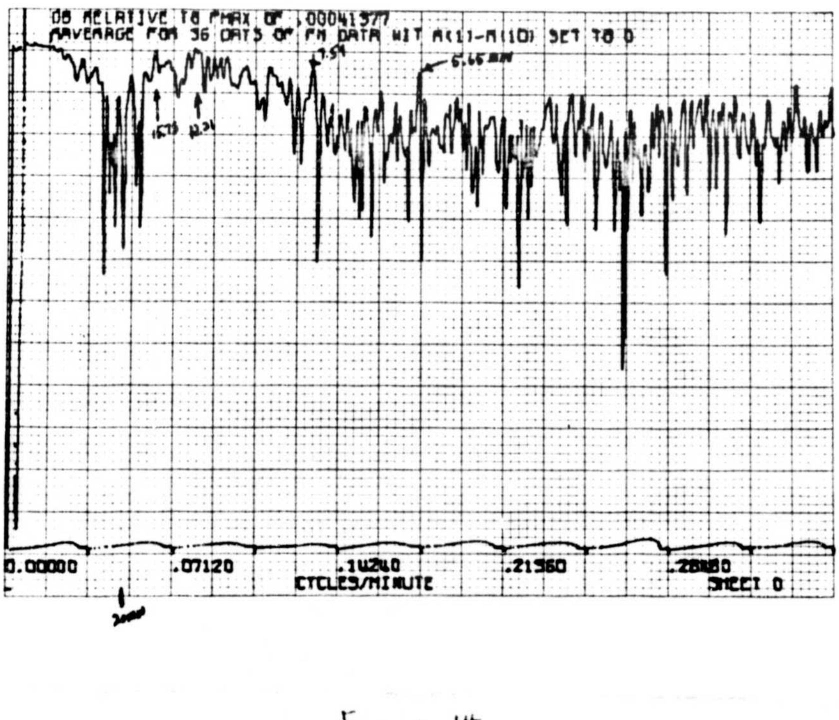


Figure 14