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LAMONT GEOLOGICAL OBSERVATORY
Columbia University
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Design and Construction of a Lunar Seismograph

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SUMMARY OF PROGRESS

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Work during this report period has emphasized preparation of design requirements for the short-period vertical seismometer to be employed as a back-up instrument for early SURVEYOR flights. A report has been prepared on this subject and is appended to this progress report.

A slightly modified version of the SURVEYOR seismograph system has been built (using other support) for use on the ocean floor during July. Acoustic telemetry will be employed for data retrieval. It is felt that experience gained in this remote operation will be useful in optimizing the operational characteristics of the four-component lunar seismograph system.

The SURVEYOR breadboard system is being prepared for long-term operation in a nearby mine where a highly stable environment exists for measurement of earth tides.

Promising results have been obtained in the development of a temperature compensating device for use on long-period vertical seismographs. This investigation is continuing.

SURVEYOR SHORT-PERIOD SEISMOGRAPH SYSTEM

INTRODUCTION

In view of the reduced payload capabilities of early SURVEYOR vehicles, Lamont proposes to develop a light weight, short-period vertical seismograph system for use on the reduced payload missions.

The seismograph will be essentially the same as the short-period vertical instrument incorporated in the full four-component SURVEYOR seismograph system. Several elements not previously associated with the short-period vertical seismograph will be included in this system.

A deployment system to provide both mechanical coupling to the lunar surface and correct orientation relative to local vertical will be included. Several deployment modes are being considered: 1) controlled drop from the spacecraft onto the surface employing a surface adaptor to permit operation near vertical. This configuration provides relatively good coupling to the lunar surface; 2) seismograph supported pendulously from spacecraft. This mode provides vertical orientation but seismic signal is subject to mechanical filtering by the spacecraft and mechanical noise eminating from the spacecraft structure; 3) seismograph fixed rigidly to spacecraft. This mode can be employed only if spacecraft orientation is guaranteed to be

within fifteen to twenty degrees of local vertical. As in orientation (2), reliable information insuring the absence of mechanical filtering and signal generation in the spacecraft would be required. Absence of firm data insuring this condition will reduce the desirability of employing modes two (2) or three (3).

Alternative possibilities also exist for locating the electronic circuitry associated with the seismograph system. The electronics can be packaged with the seismometer itself or in the thermally controlled spacecraft electronics chambers.

The latter location is preferred since it minimizes the thermal control requirements imposed on the seismograph unit. However, if the acceptability of the seismograph as a back-up instrument hinges on minimizing the spacecraft modifications required for its installation, it may be advisable (and is feasible) to build the electronics into the seismograph package.

It is felt that fabrication of two prototype units at this time would satisfy all the immediate requirements for environmental and operational testing.

The design, fabrication, and test program can be completed within a period of seven (7) months.

I. MECHANICAL SYSTEM

A. FUNCTIONAL DESCRIPTION

The short-period vertical seismograph system proposed for use on the reduced weight SURVEYOR spacecraft consists of the following:

1. A short-period vertical seismometer with free resonant period of 1.3 seconds, equipped with a moving magnet velocity transducer and associated electronic circuitry. Maximum gain is 125 millivolts per millimicron at 1 cps.

2. A thermal control system employing passive elements (super insulation) or passive plus active elements (super insulation and heating).

3. A caging mechanism to prohibit relative motion between the seismometer elements during periods of vibration and impact. Items 1, 2 and 3 are visable in Figure 1.

4. A surface adapter and a deployment mechanism consisting basically of a tripod from the top of which the seismometer is suspended and a device to lower the entire system onto the lunar surface.

5. Mechanical interface elements for attachment of the seismometer to the spacecraft and separation during seismometer deployment.

B. DETAILED DESCRIPTION

1) Seismometer

The mechanical structure is composed basically of four elements: 1) a cylindrical magnet assembly weighing 1670 grams

forming an annular gap; 2) a fixed, center-tapped cylindrical coil, with winding impedance of 2000 ohms, centered within the magnet gap. Several turns of wire are wound on the same form, but independent of the main coil, for instrument calibration; 3) the elastic suspension, consisting of two pre-formed copper beryllium springs .010"thick; and 4) a cylindrical housing approximately 4.5 inches in diameter and 4 inches high.

Maximum weight economy is obtained by suspending the magnet assembly itself as the seismic mass. The cylindrical magnet is surrounded by a soft iron cup which serves as the return flux path and as a shield for the magnet. Magnetic induction in the gap is approximately 4000 Gauss. Gain settings of 1.25, 12.5 and 125 $\frac{\text{millivolts}}{\text{millimicron}}$ are available. An auxiliary spring is provided to support five-sixths of the mass for test operation in the earth's gravitational field.

2) Thermal Control System

Temperature control is achieved by a thermal shield which completely encapsulates the seismometer.

Several types of super insulation are available for the thermal shield: 1) multiple laminations of aluminized mylar; and 2) alternately laminated aluminum foil and fiberglass sheets are two possibilities. This passive thermal control may be augmented by heat supplied to the system at appropriate times in the temperature cycle. In order to minimize heat flow across the insulation, a thermal restriction will be employed to carry leads through the insulation.

The springs may be converted from the standard copper beryllium to another material (e.g., isoelastic) with a much lower thermoelastic modulus if thermal drift of the mechanical center position becomes a limiting factor on the allowable temperature range. A temperature sensor is included in the system.

3) Caging Mechanism

Caging is performed by clamping the seismometer mass against the support frame. The actuators are pneumatic bellows spring loaded for the uncage cycle. Actuation is performed by a clean 50 psi air source through a standard tire valve. Uncaging may be performed by pressing the valve stem or, on command, by actuating a dimple motor (squib device) which drives a steel pin through a .002 inch diaphragm in the pressurized system, rupturing the diaphragm, releasing the caging pressure, and allowing the mass to swing free.

Several alternative actuators may be considered.

4) Deployment and Surface Adapter

The deployment cycle is performed after preliminary spacecraft operations are completed. The seismometer is attached to a tripod in such a manner as to permit it to swing to a vertical position after reaching the surface independent of the local conditions beneath the three legs. The lowering rate (not yet defined) is controlled by an escapement mechanism attached to the spacecraft.

5) Mechanical Interface

Attachment of the seismograph system to the spacecraft will be done by retractable pins which can be withdrawn at deployment. Some structural elements will be added to the spacecraft to provide pin support points.

II. ELECTRICAL SYSTEM

A. General Description

Basically, the short-period seismometer consists of a coil mounted within the flux gap of a suspended permanent magnet, which serves as the inertial mass. An auxiliary coil is wound on top of the main one, for calibration purposes. Motion of the suspended magnet relative to the stationary main coil induces a voltage proportional to the differential velocity. The response of a properly damped seismometer is essentially flat to ground displacement for frequencies above its natural frequency and to ground acceleration below its natural frequency. Since the velocity transducer output differentiates this motion, its output is flat to ground velocity above the natural frequency. If the amplifier is flat over the specified range, then the overall system response is that of the instrument itself, in the above frequency range. A very high gain, low noise amplifier is required to increase the minute amounts of seismometer output power up to the levels required by telemetry.

Without any knowledge of background seismic noise (microseisms) on the moon, it is impossible to decide on exactly what gain to use in the amplifier. In general, the moon is thought to be much quieter than the earth, and maximum possible gain might be thought appropriate. If, however, this is not the case, a high gain amplifier could saturate on background alone. Two solutions to this problem exist: a non-linear amplifier and an amplifier with gain adjustable on command. The second solu-

tion was chosen in this case and a step attenuator incorporated in the amplifier.

In view of the extremely low frequencies involved, the chopper-amplifier is probably the best choice in seismic work Very low noise levels may be achieved with good mechanical or photoelectric choppers. These, however, had to be ruled out in this case because of power limitations and environmental requirements.

Solid-state choppers, on the other hand, do not offer much promise in achieving the desired noise levels.

A compromise was reached in a design that employs a solid-state chopper-amplifier preceded by a direct-coupled, low-noise preamplifier with a single, low-frequency coupling between the two. Thus D-C drift from the preamplifier is not amplified further by the carrier amplifier. The complete circuit block diagram is shown in Figure 2. In order to utilize the advantages of a balanced arrangement in the preamplifier, the seismometer main coil was center-tapped, thus providing a push-pull output. The output of the preamplifier is filtered and applied to the modulator followed by another stage of push-pull amplification. The modulated signal is then applied, through the attenuator to the following stages of A-C amplification. It is then demodulated and filtered.

B. Detailed Description

Preamplifier

The preamplifier consists of two direct-coupled differential stages with overall direct feedback. The feedback stabilizes the operating point, the current gain, and the input impedance presented to each half of the center-tapped transducer coil. The amount of feedback is chosen to adjust the amplifier input impedance to that required for damping the seismometer without use of an external damping resistor. Thus the maximum amount of power is transferred to the input of the amplifier.

A complete analysis of the gain of the circuit shows that for the worst possible combination of parameters the voltage gain may vary from 430 to 980 about a design center value of 600. Thus, despite the fact that the input impedance is largely determined by feedback rather than transistor parameters, the spread is considerable, ranging from approximately +40% to -38%, about a design center value of 840 ohms.

Since damping is inversely proportional to the sum of transducer impedance plus amplifier input impedance, the variation of damping will be a function of the variation of the above two parameters. If transducer and amplifier are in the same temperature environment, then it is possible to incorporate some form of compensation in the circuitry.

Modulator

The balanced output from the preamplifier is coupled through an appropriate filter to a half-wave bridge modulator consisting

of four matched diodes in a single package. The balanced output of the modulator is then fed into a push-pull amplifier which provides an amplified full-wave version of the modulator waveform. The gain of this stage is stabilized through emitter resistors which, at the same time, provide a convenient means of nulling carrier leakage at the output. This is done by padding either of these resistors with an appropriate resistance value to obtain the best null. The transistors employed in this stage are available in matched pairs in the form of a duo-transistor in a single TO-5 case. The output transformer primary is tuned to the carrier frequency and some improvement in gain and phase is thereby effected. The secondary of the transformer is biased to a positive voltage. This is required for the proper operation of the step attenuator which follows this stage. The overall gain of the modulator and push-pull amplifier is approximately equal to ten.

A-C Amplifier

This amplifier consists of two direct-coupled stages feeding the transformer-coupled demodulator. The operating points and gain are stabilized through separate D-C and A-C feedback loops.

The operating point of the second stage is chosen to provide the maximum swing into the output load which is effectively the feedback resistor, since the demodulator input impedance is very high. The operating point of the first stage is determined by the emitter voltage of the second since direct coupling is

employed. The base bias for the first stage is derived from a tap in the emitter resistor of the second stage. This arrangement, together with the large emitter resistor of the first stage results in an extremely stable amplifier.

A complete analysis of the A-C gain of the circuit shows that for the worst possible combination of transistor parameters the open-loop gain may vary from 850 to 5800 over the temperature range of $-20^{\circ}C$ to $+100^{\circ}C$. If the feedback factor is B = .01, then the corresponding variation in closed-loop gain is 89.5 to 98.2 with a design center value of 96. Thus the gain may be specified as:

$$A = 96 \begin{array}{l} +2.3\% \\ -6.8\% \end{array}$$

Demodulator

The demodulator is a half-wave diode bridge arrangement. The four diodes are of the same type as those used in the modulator. The output is fed to an emitter follower that provides a high impedance to avoid loading of the demodulator. A second emitter follower at the output of the first offers some degree of temperature compensation due to the NPN-PNP transistor arrangement.

A low-pass RC filter is inserted at this point to suppress high frequency components of the demodulated signal.

Step Attenuator

It is desirable to maintain the calibration output pulse at a constant percentage of full-scale reading independent of the

gain setting. This can be done by inserting an attenuator which varies inversely as the gain setting, between the calibrate pulse generator and the auxiliary seismometer coil.

A circuit was designed which performs this function upon reception of the appropriate command trigger. As shown in block diagram form (Fig. 3) the circuit consists of two flip-flops driving four transistor switches. Attenuator I is the amplifier gain attenuator and attenuator II is the attenuator of the calibrating voltage. A total of three steps of gain change can be obtained as follows:

Trigger #1 resets FFA and FFB to the states shown. Thus S_1 and S_2 are open and S_3 and S_4 are closed. This is the position of maximum amplifier gain and minimum calibrating voltage size. Trigger #2 reverses the state of FFA only, thereby closing S_2 and opening S_3. This is the position of intermediate gain and calibrating voltage size. Finally, Trigger #3 reverses the state of FFB only, thereby closing S_1 and opening S_4. This is the position of minimum gain and maximum calibrating voltage. The sequence is not reversible in that if it is desired to change from minimum to intermediate gain, one must go through maximum (reset) gain first. The attenuation factors attainable are only limited by the ON and OFF resistances of the transistor switches. A very large attenuation would necessitate a very small value of R_2 and is eventually limited by the saturation resistance of transistor S_1.

The input A-C signal must be polarized for proper functioning of the switches.

Direct-coupled transistor triggering of the flip-flops makes performance independent of trigger characteristics.

The attenuator flip-flops are "worst case" designs and will function properly throughout the temperature range.

Calibrator

The calibrator is simply a flip-flop which, when triggered by a command pulse, produces a current step in the auxiliary coil of the instrument. The step is subsequently turned off by another command pulse after a satisfactory transient at the output is obtained. The advantages of such an arrangement over a free-running pulse generator are obvious and need not be discussed further.

As discussed previously, the size of the step is inversely proportional to the gain. Thus the output pulse amplitude is independent of gain setting. The peak amplitude of the output transient is approximately 25% of full scale.

C. Experimental Results

Several units of this amplifier were built, for laboratory testing and field use. The results of operational and environmental testing indicate that the design goals have been met or exceeded. Some representative experimental graphs and figures are included.

Figure 4 shows the performance of the step attenuator adjusted to give 20 db steps of gain change. For any particular setting, the performance is substantially linear over the required dynamic range.

The amplifier was subjected to a temperature test at maximum gain. The output drift shown in Figure 5 is the combined result of carrier leakage in the modulator, temperature drift in the demodulator, and the small variation of carrier amplifier gain.

The frequency response of the amplifier is plotted in Figure 6. The 3 db frequencies are .035 cps and 22 cps. Other bandwidths can readily be achieved by changing the values of a small number of components. Figure 7 shows the output noise achieved with an overall gain setting of 0.5×10^6, recorded at several speeds. It is seen that for 90% of the time the output noise does not exceed 100 mv, which corresponds to an equivalent input noise of 0.2 μv p-p.

A noise figure measurement is not very meaningful in seismic work. A better estimate of the capabilities of the amplifier can be obtained by examining the output waveforms of Figures 8 and 9. These correspond to respective inputs of one, and one-quarter microvolt p-p, obtained with the same recorder sensitivity and speeds as in Figure 7.

In particular, a 1 cps input of 1/4 μv is detected with an S/N ratio of about 4:1. Since the transducer sensitivity is 0.6 μ/mm p-p at 1 cps, it appears possible to detect 1 Angstrom

($10m^{-10}$) p-p ground motion at 1 cps with unity S/N ratio.

It should be emphasized at this point that, except for matching, no other selection of input transistors was made. Noise measurements on other units gave results that were substantially identical to the above.

Figure 10 is a seismic record obtained with a four-component seismograph. The bottom trace in the record is the short-period vertical instrument with the amplifier operating at minimum gain. Pertinent information is included on the record.

III. INTEGRATION INTO SPACECRAFT

A. Location of Electronics

Several alternative electronic packaging arrangements are feasible:

1) The electronics can be part of the seismometer unit, in which case, the allowable temperature range of the seismograph is limited by the allowable electronics temperature range;

2) The electronics can be located in the thermally controlled spacecraft electronics compartment. In this case, electronic components do not limit the acceptable seismometer temperature range. A change in temperature of $\pm 75^{\circ}C$ produces a change of $\pm 15\%$ in the damping ratio which is not considered serious.

The second alternative seems most attractive at this time. However, if integration requirements indicate major modifications in spacecraft systems, the first alternative can be employed with a minimum of spacecraft readjustment.

B. Seismograph Location, Deployment

Several alternative modes of operational orientation of the seismograph are considered.

The preferred operational mode at this time is similar to that employed in the four-component system. In this mode, the seismograph is lowered from the spacecraft to the lunar surface where it is suspended from a tripod. This mode is preferred since it provides the best coupling of the seismograph to the lunar surface. In this mode, the seismograph orientation rela-

tive to the lunar gravity vector is optimized.

In two alternate modes, the seismograph would be permanently fixed to the spacecraft. In one case, the seismograph is suspended pendulously from a mounting point on the spacecraft. In the second alternate mode, the seismometer is rigidly attached to the spacecraft. In this mode, the seismograph may operate as much as 15° to 20° off level. These modes require successively fewer spacecraft modifications and provide successively less desirable seismometer orientation.

IV. SPECIFICATIONS

A. ELECTRONIC

1. Power Requirements

a. Regulated voltages: +12 volts (±5%)
+24 volts (±5%)
-6 volts (±5%)

(Total ripple and noise of above voltages not exceeding 0.5%).

b. Power: 150 milliwatts, with the following breakdown:

4.5 mA at +12 volts
3 mA at +24 volts
4 mA at -6 volts

2. Output impedance: below 500 ohms.

3. Output level: 2.5 volts DC nominal with a 0-5 volt swing capability.

4. Maximum output sensitivity: 125 millivolts/millimicron ground displacement at 1 cps.

5. Long-term stability: within 5% of full scale.

6. Linearity: within 10% of best straight line.

7. Equivalent input noise: does not exceed 0.2 microvolt p-p for 90% of the time.

8. Frequency response: 1/30 cps to 20 cps, nominal; (other passbands may be readily obtained).

9. Commands required: Deployment

Uncage (1 or 2)

Power ON

Power OFF

Gain change (3)

Calibration ON)
) none if automatic
Calibration OFF)

10. Cabling (Electronics in spacecraft)

3 - main coil
1 - calibrate
3 - uncage (for 2 squibs)
1 - case ground shield
2 - temperature sensor
10

B. MECHANICAL SPECIFICATIONS

1. Temperature Stability

Tested over temperature range -30°C to 80°C

Displacements ±.1" from center position

(total operating range is ±.375")

Period variation negligible

Damping variation - acceptable

2. Thermal Control Required

a) Should operate satisfactorily about any reasonable mean ±50°C

b) Passive Control - superinsulation

c) Active Control - small amount of heating may be useful depending on design employed

3. Off Level Tolerated

Total range available ±3/8" (.375")

±15° off level causes ±0.16 inch displacement

±20° off level causes ±0.28 inch displacement

4. Possibility of Mounting Seismograph on spacecraft permanently

a) Advantages: light weight; no Deployment; mount anywhere

b) Disadvantages:

1) Spacecraft mechanical noise
2) Spacecraft may filter seismic signal - very little data available on spacecraft resonances
3) Operation off vertical (max. ±15-20°)

5. Caging

   Present system satisfactory - minor modifications possible

6. Physical Dimensions

   a) Length - 5 inches

   b) Diameter - 4.5 inches

   Surface adapter, insulation, vibration and impact protection additional

7. Deployment Methods

   Escapement as employed with full four-component system or alternative mechanism - requirements less stringent

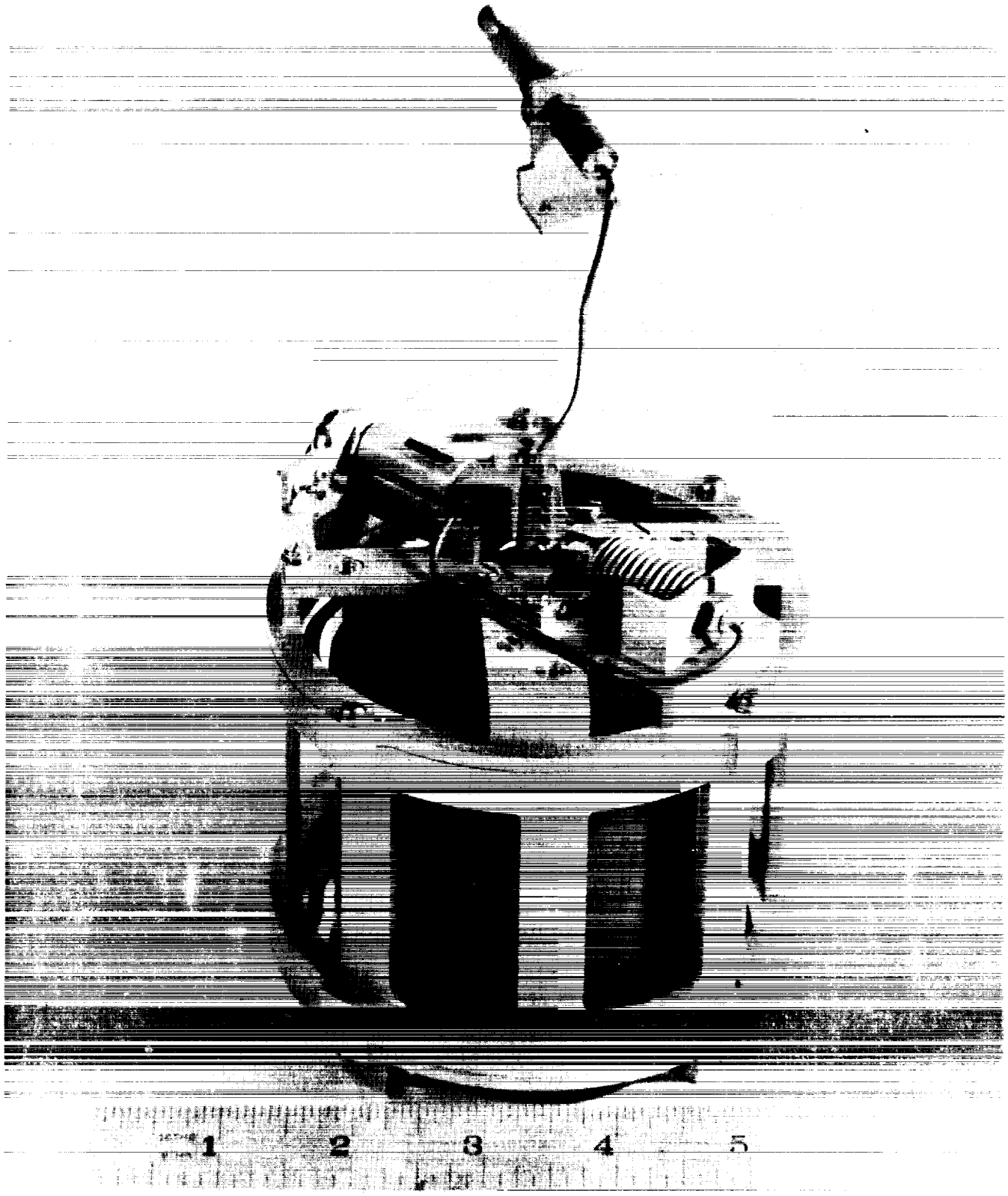
8. Surface adapter

   Many alternatives - tripod (likely choice), legs, hemisphere, pendulum

9. Weight

   a) Seismometer with caging - 4.4 lbs. (present system)

   b) Estimate total system weight six to eight pounds (6-8 lbs.) including electronics, surface adapter, insulation, vibration and impact protection and spacecraft attachment elements.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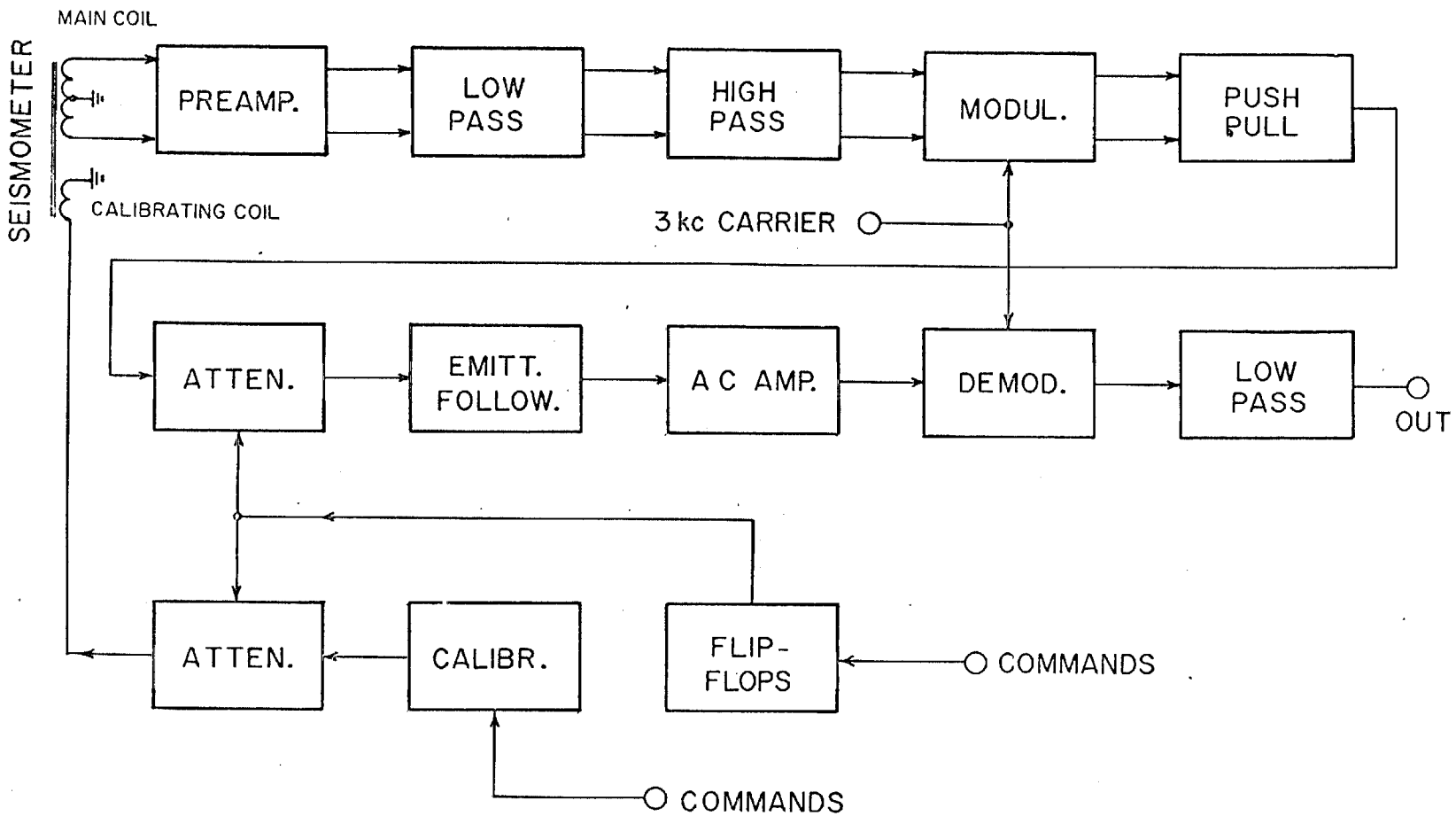
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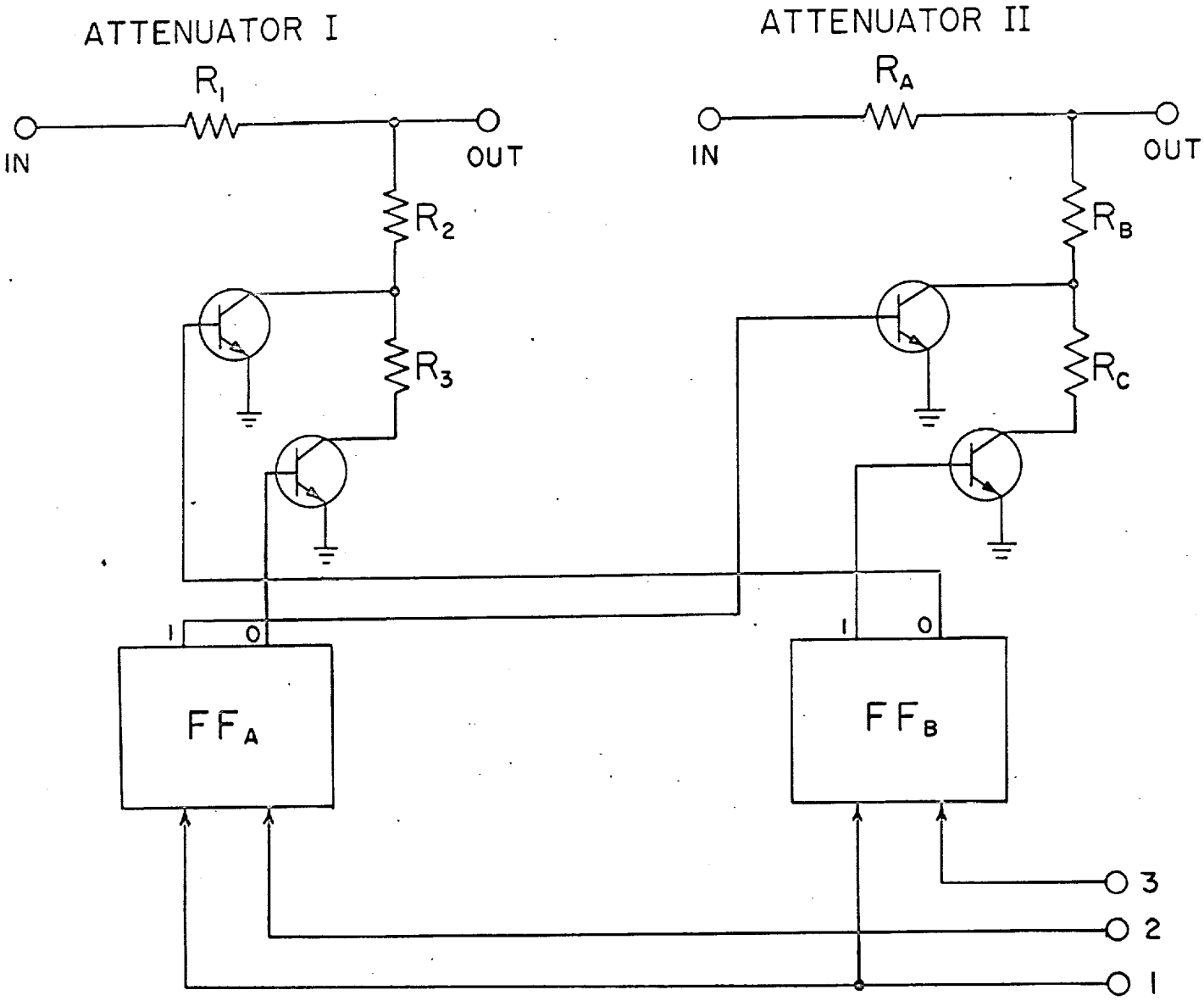
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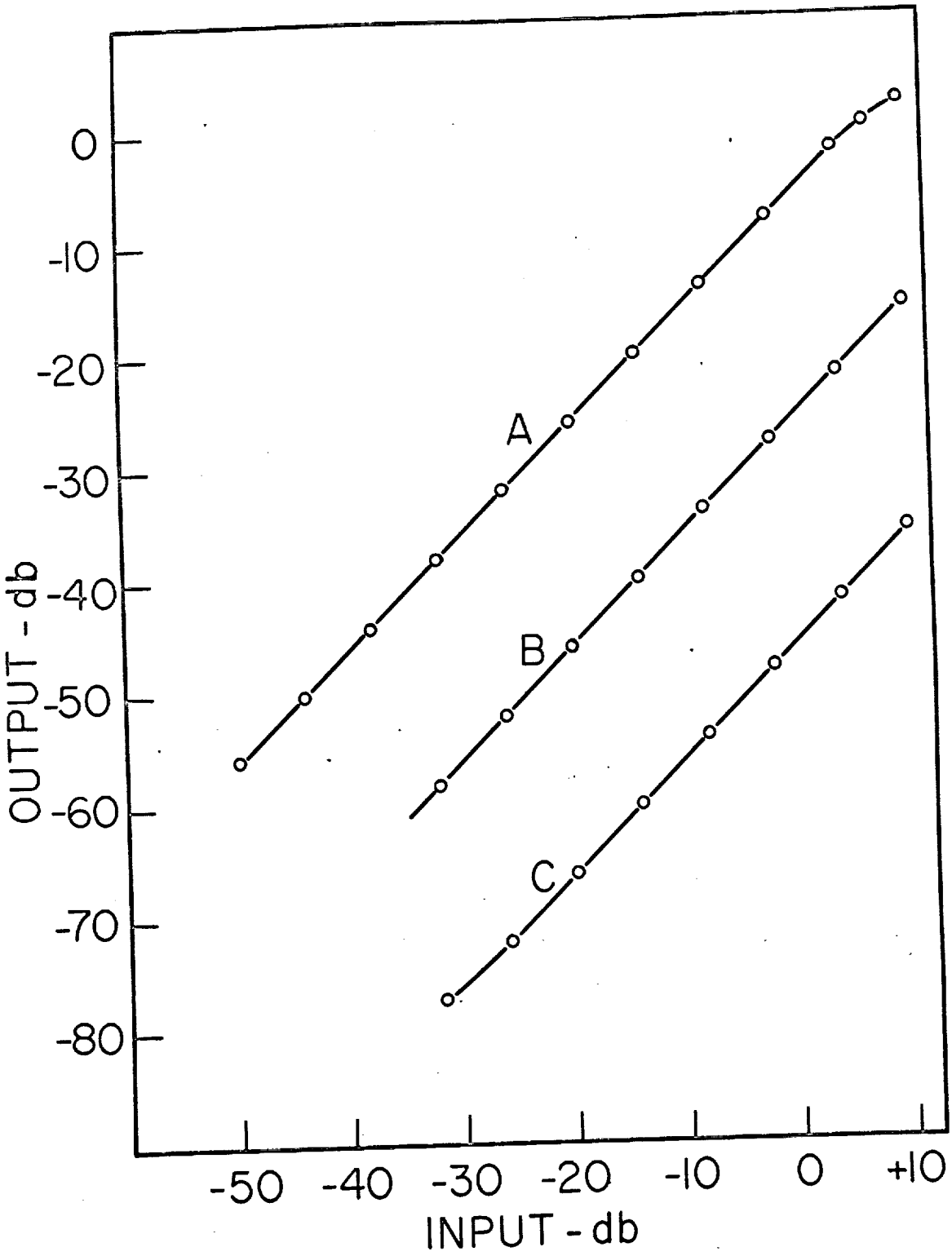

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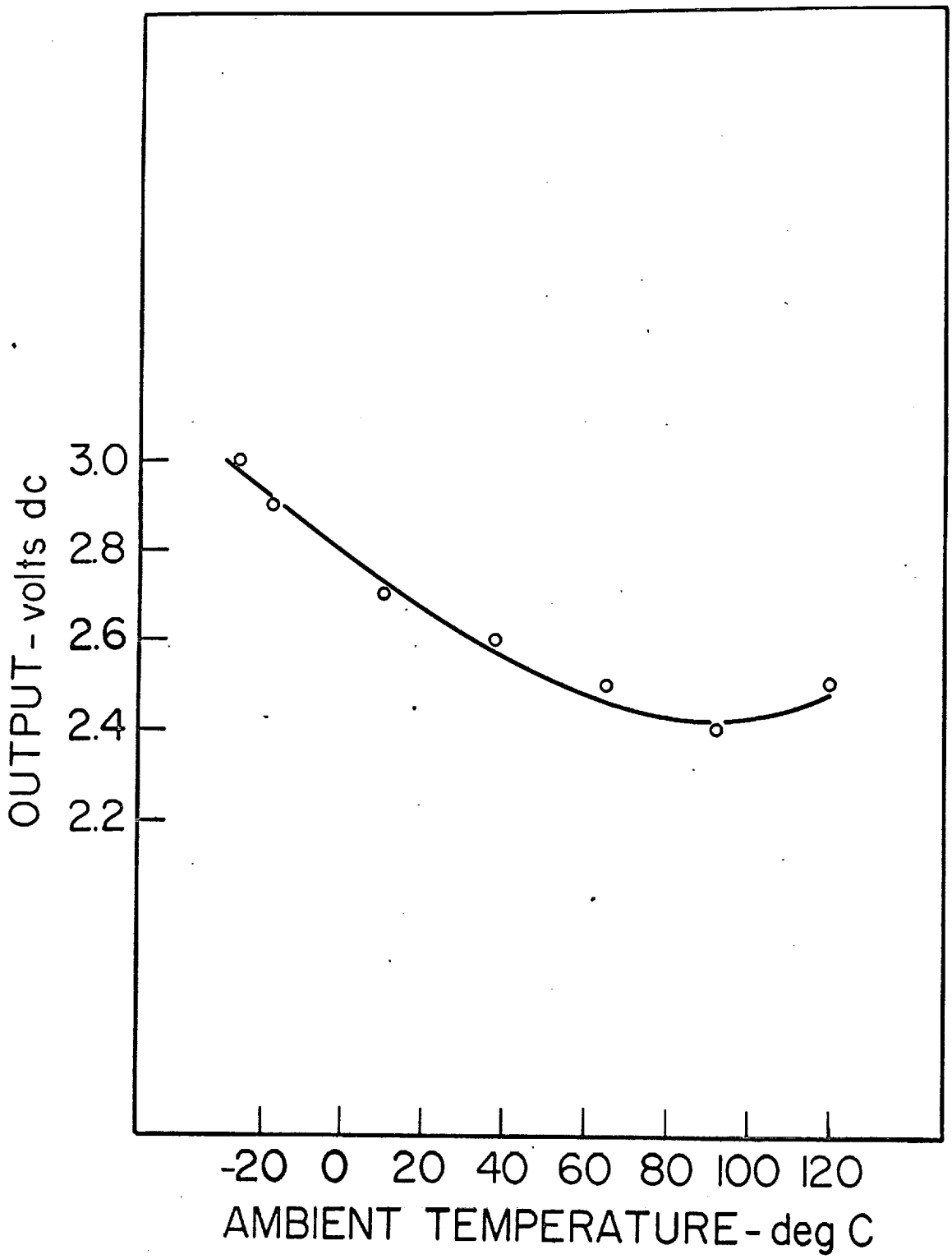
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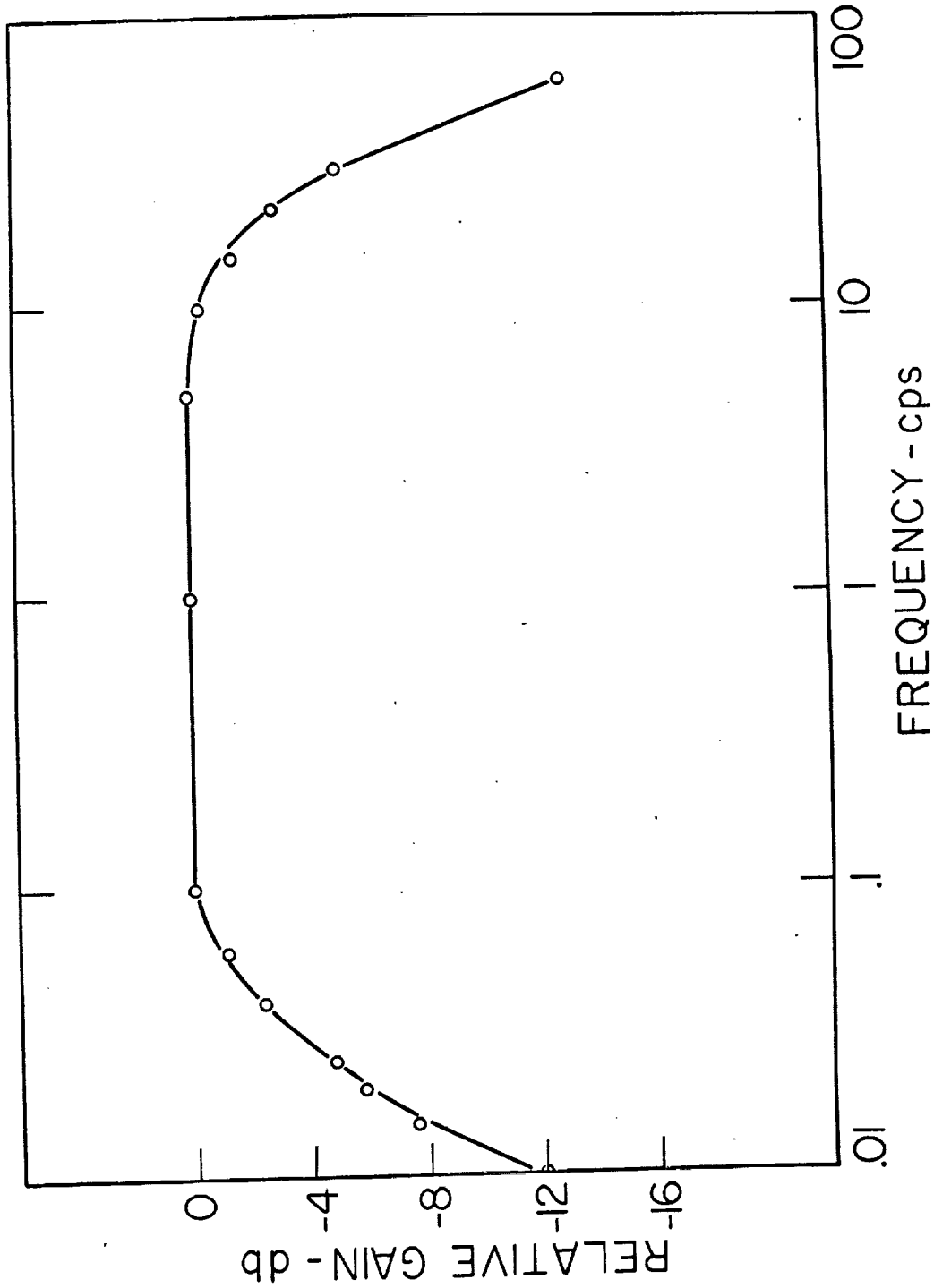

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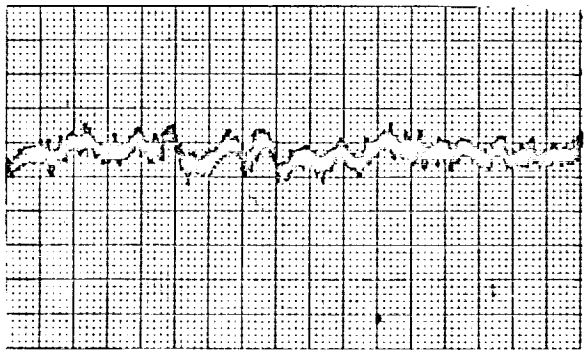
Fig. 7 Output Noise of the amplifier with an overall gain of 1/2 million. Recorder sensitivity is 200 mv/cm and speed is (A) 0.5 mm/sec, (B) 1 mm/sec, (C) 10 mm/sec, (D) 100 mm/sec.

Fig. 8 Amplifier output waveforms for an input of 1 uv p-p of frequencies (A) 0.05 cps, (B) 0.1 cps, (C) 1 cps, (D) 10 cps. Recorder sensitivity is 200 mv/cm.

Fig. 9 Amplifier output waveforms for an input of 1/4 uv p-p of frequencies (A) 0.05 cps, (B) 0.1 cps, (C) 1 cps, (D) 10 cps. Recorder sensitivity is 200 mv/cm.

A



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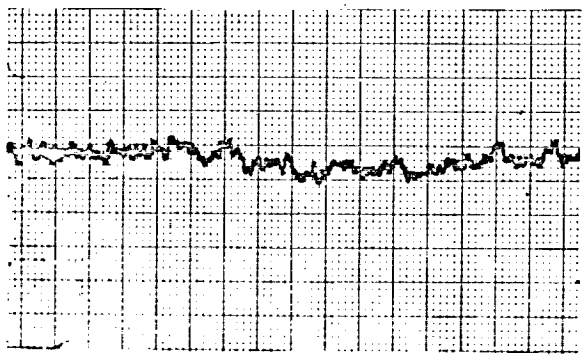

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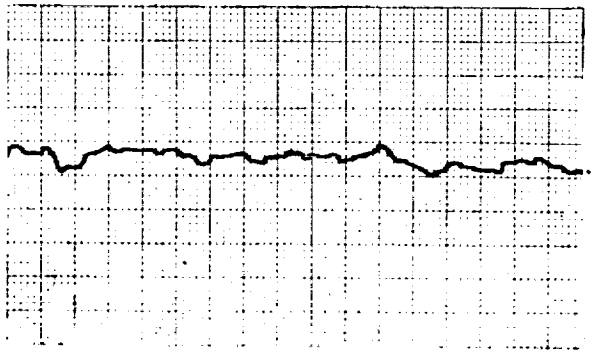

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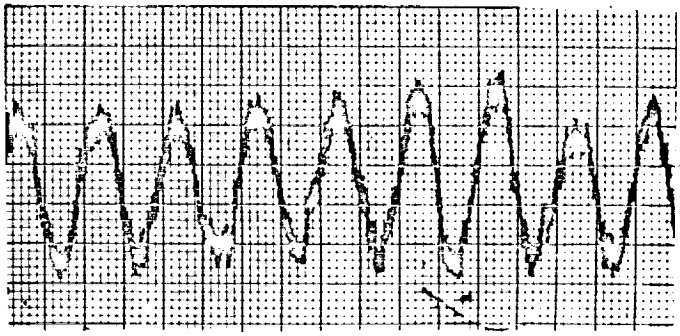

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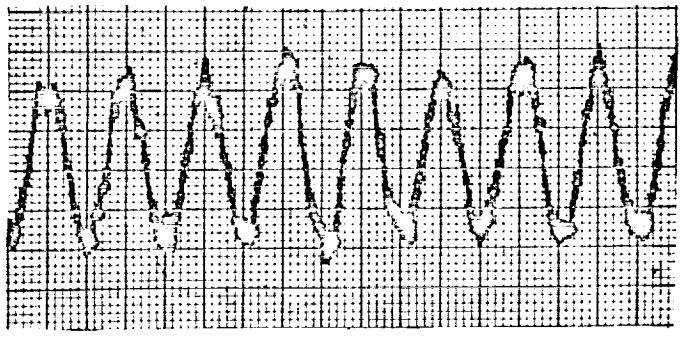

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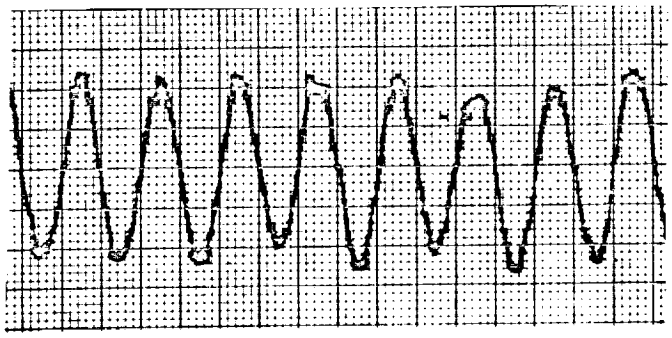

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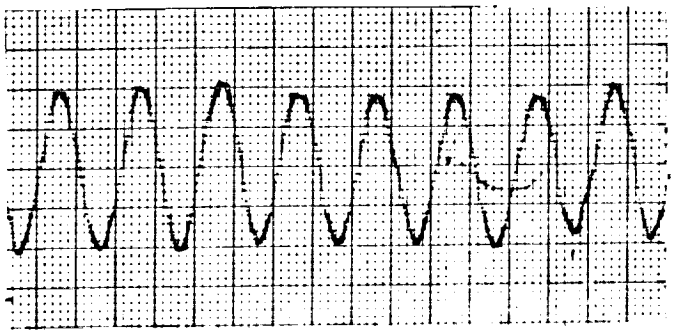

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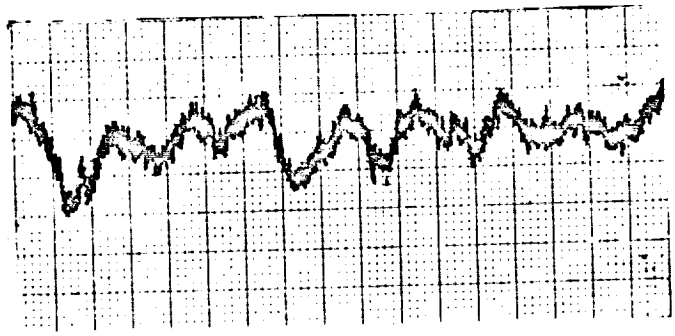

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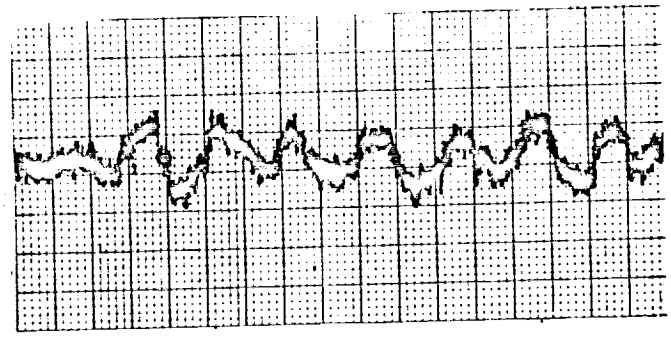

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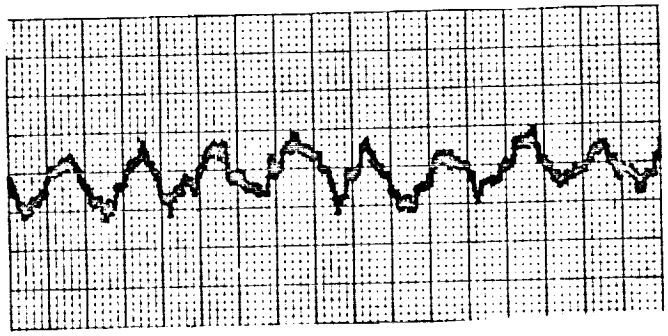

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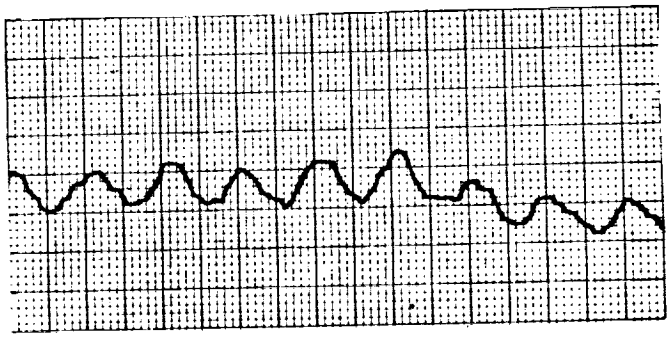

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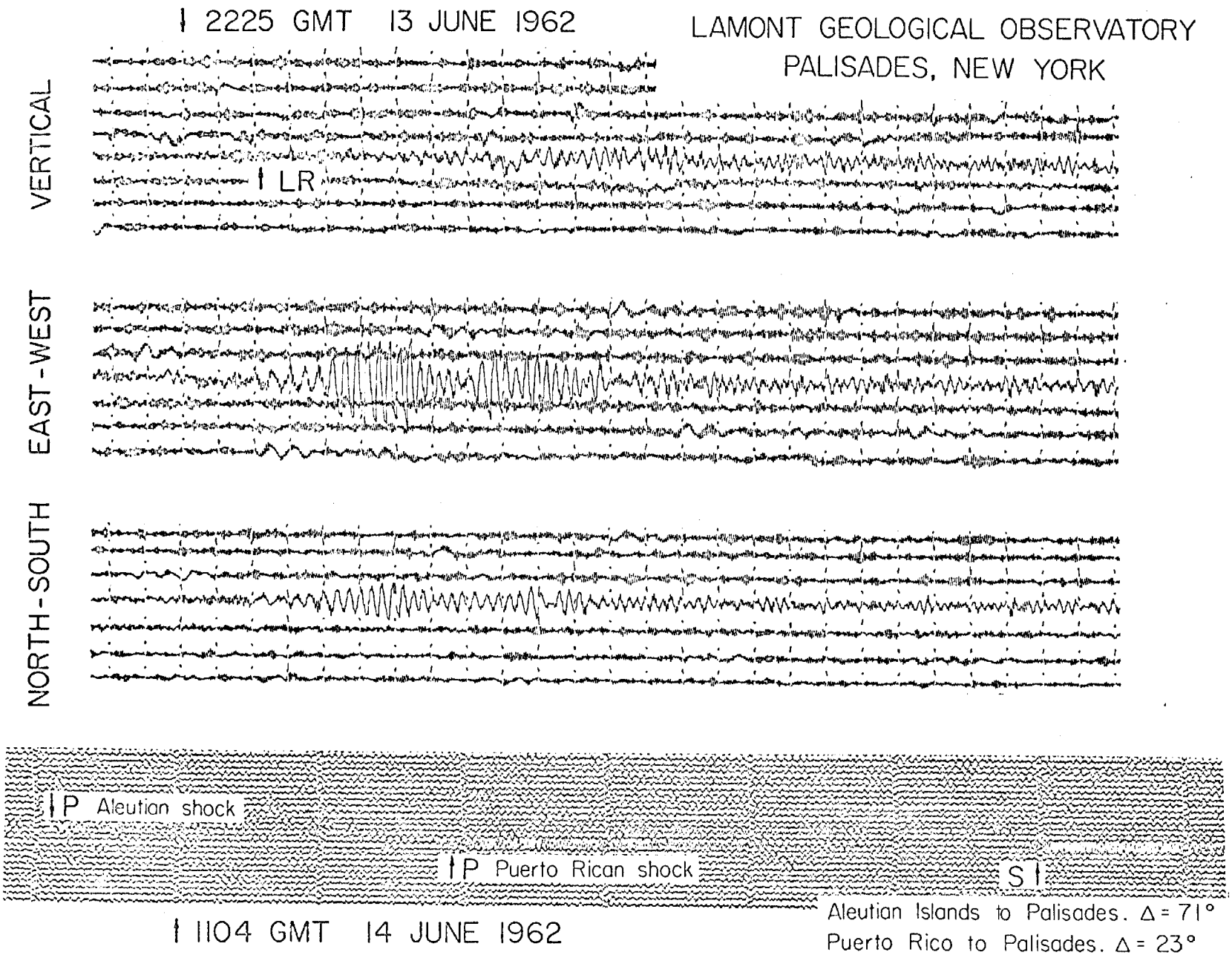

Aleutian Islands to Palisades. Δ = 71°
Puerto Rico to Palisades. Δ = 23°
Recorded by four-component
lunar Seismograph.