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TECHNICAL REPORT NO. 66-94

LONG-PERIOD SEISMOGRAPH DEVELOPMENT

Quarterly Report No.1, Project VT/6706

TELEDYNE INDUSTRIES
GEOTECH DIVISION
GARLAND TEXAS

TECHNICAL REPORT NO. 66-94

LONG-PERIOD SEISMOGRAPH DEVELOPMENT

Quarterly Report No. 1, Project VT/6706

by

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CONTENTS

ILLUSTRATIONS

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TABLES

ABSTRACT

Equipment was designed and constructed to perform a thermal noise experiment. The objective of the experiment was to experimentally investigate the spectral distribution of noise energy in seismometers and galvanometers and their interconnections. The equipment used in the experiment is described. Final results are not given but will be included in a forthcoming final report.

A long-period triaxial borehole seismometer was designed. The design has preserved ideal "La Coste" geometry in that changes in period are accomplished through a controlled positive restoring force rather than through alteration of the geometry. Also, temperature compensation is designed to preserve the geometry. The seismometer is designed such that it will withstand shipping and installation acceleration while completely assembled.

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LONG-PERIOD SEISMOGRAPH DEVELOPMENT

1. INTRODUCTION

This report discusses a thermal noise experiment and the development of a long-period triaxial borehole seismometer. Final results of the noise experiment will be reported in the final report of the task. This report does not include two tasks of the statement of work because these tasks (field testing and analysis of data) cannot be started until the triaxial seismometer is completed.

The purpose of this report is to present the technical accomplishments of this project for the period from 15 May 1966 through 30 September 1966; it is submitted in compliance with paragraph 2, Data Requirements, of the Statement of Work to be done, AFTAC Project Authorization No. VELA T/6706 dated 15 February 1966. The project is under the technical direction of the Air Force Technical Applications Center (AFTAC) and under the overall direction of the Advanced Research Projects Agency (ARPA).

2. EXPERIMENTAL INVESTIGATION OF THERMAL NOISE, TASK 1a

2.1 INTRODUCTION

Thermal noise in a seismometer comes from several different sources. It may result from the irregular bombardment of air molecules on the mass, the random movement of electrons in the electrical circuit, and random fluctuations in the magnetic-field strength in the air gap of the magnet. Any loose elements, such as resistors or dashpots, which are coupled to the spring-mass system of the seismometer will act as noise sources. The coupling of any other system to a spring-mass system will not alter the long-term average of the kinetic or potential energy of the spring-mass system if the temperatures of the two systems are equal. Any change in the long-term average energy of the spring-mass system would mean that energy was exchanged by two systems initially at the same temperature. Such an exchange would violate the second law of thermodynamics.

While the long-term or rms value of the noise energy of a spring-mass combination is independent of its coupling to other systems which are at the same temperature, the spectral distribution of the noise energy is not necessarily independent of the coupling.

Consider a seismometer or galvanometer which is damped at some value by a combination of air and electrical damping. If the air damping is removed and the electrical damping increased so that the total damping remains the same, the rms value of the noise energy will not be altered. However, it is possible that the spectral distribution of the noise energy may be different. As another example, consider two identical moving-coil seismometers at the same temperature and damped at the same value. Let one be coupled to a resistive load, and the other to a galvanometer. Again, the rms value of the thermal noise of the two seismometers will be the same, but the spectral distribution of this noise energy may not be the same.

While it is true that much theoretical and experimental work has been done on thermal noise, most of this work has been to confirm that its value is $1/2\ kT$ for each coordinate required to describe the position and momentum of a system, where k is Botzmann's constant and T is the absolute temperature. This fact applies for any system, and as previously stated, is independent of coupling. Since the spectral distribution is a function of coupling, it can only be investigated for a specific case.

The purpose of the experimental investigation of thermal noise is to investigate the spectral distribution of noise energy in seismometers and galvanometers and their interconnections. Subsequent comparisons of the thermal-noise spectrum with a typical seismic-noise spectrum will enable the ultimate magnification of a typical seismograph to be expressed in terms of its various parameters. The faith of the engineer and seismologist in these data will be increased considerably by the experimental verification of theoretical thermal-noise spectral distributions.

The experimental effort in this investigation is divided into two parts called experiment 1 and experiment 2. Experiment 1 was designed to determine the spectral distribution of thermal-noise energy in a seismometer or galvanometer with a resistive load. The purpose of experiment 2 is to verify the spectral distribution of thermal-noise energy in a seismometer-galvanometer combination.

Torsion pendulums are being used in experiment 1 and a special galvanometer in a torsion pendulum housing was conceived for use in experiment 2. The pendulums are described in detail in Geotech Technical Report 64-127, Interim Report On The Experimental Investigation Of Thermal Noise, Project VT/072, and the effort expended to complete the pendulums, as well as other efforts on this task, are described below.

2.2 PROGRESS

During the report period, work was expended to complete the following efforts: literature search for previous applicable work; overall planning and layout for all experimental aspects of the task; layout, design, and fabrication of special optical system required; assembly of the torsion pendulums; design and construction of a special galvanometer suspension and armature suitable for inclusion in a torsion pendulum housing; and design and fabrication of the magnetic structures required for pendulum and galvanometer damping.

The literature search revealed a number of papers and developments directly related to seismograph analysis as well as earlier papers more general in nature. The directly related work includes the following:

Matheson, H. and Gilbert, W., On the Frequency Distribution of Brownian Motion (unpublished)

Byrne, C. J., Jan 1961, Instrument Noise in Seismometers, Bulletin of the Seismological Society of America, vol. 51, no. 1, p. 69-84

McCoy, D. S., various reports on thermal noise written under Contracts AF 49(638)-1080 and AF 49(638)-1456

The earlier papers include the following:

Johnson, J. B., July 1928, Thermal Agitation of Electricity in Conductors, Physical Review, vol. 32, p. 97-109

Nyquist, H., July 1928, Thermal Agitation of Electric Charge in Conductors, Physical Review, vol. 32, p. 110-113

Barnes, R. B., and Silverman, S., July 1934, Brownian Motion as a Natural Limit to All Measuring Processes, Reviews of Modern Physics, vol. 6, 162 p.

Milotz, J., and Zolingen, Physics 19, 181 (1953) The Brownian Motion of Electrometers

Landon, U. D., February 1941, The Distribution of Amplitude With Time in Fluctuation Noise, Proc T. R. E., p. 50-55

All of the above listed papers and developments have been at least briefly reviewed and those directly related to seismic instrumentation have been examined in considerable detail.

In order to conduct the experimental work, a laboratory was selected and prepared. The selected laboratory has controlled access so that personnel traffic may easily be limited and has a large pier for placement of the optical system.

Control equipment such as function generators, recorders, and signal conditioning amplifiers are located in an adjoining room, and all calibrations and adjustments are made without entering the laboratory and disturbing the sensitive instruments. Signal conditioning amplifiers were designed and constructed around commercial operational amplifiers such that signals from equipment on the pier can be properly matched to any reasonable recorder system. The recorders used for the experimental work are a Brush 240 modular recording system and a Honeywell magnetic-tape system. A block diagram of the complete experimental layout is shown in figure 1.

Figure 2 shows a simplified layout of the special optical system that was designed and fabricated. The solid line indicates the optical path for the desired noise data and the broken line indicates the optical path during system static-noise checks and calibration. During data acquisition when using the torsional pendulums, coherent inputs to the pendulums are optically cancelled and the remaining system output results from incoherent, thermal noise. During system static-noise checks the input to the test galvanometer is effectively shorted and the resulting system output is due to excess electronic noise. This check is performed routinely to ensure that excess electronic noise is not of sufficient magnitude to cause errors. To calibrate the system a low level input is fed to the test galvanometer, which has been previously calibrated, and the resulting signal is recorded. From this information system calibration in output-voltage-per-unit-rotation is obtained.

The change from data acquisition to noise-check and calibration is accomplished by inserting a large mirror in the optical path between the torsional pendulums and the light source. This large mirror is shown in figures 3 and 4 along with the other optical components. The light source for the system is composed of an incandescent lamp and two lenses. This source is the long, light colored tube assembly seen on the left in figure 3. The conversion from optical signals to electrical signals is accomplished with beam-splitter and phototube-deck assemblies from a Model 4300 phototube amplifier. These assemblies are shown in figures 3 and 4. The mirrors used in the optical system are 1/4 wavelength and the lenses are achromatic.

Preliminary fabrication of the torsional pendulums was completed. This consisted of completing pendulum parts, carefully cleaning all parts, selecting the quartz suspension fibers, assembling the pendulums, and verifying that the natural period of each of the pendulums was correct. A natural period range of 8 to 25 sec was selected with 10 sec as a goal. The periods of all the pendulums will be the same and tests indicate that these periods will be about 10.5 sec. After preliminary fabrication the pendulums were disassembled to coat the quartz sphere armatures with silver. This coating was required so that the pendulums can be damped by an externally originating magnetic field. One of the most severe problems encountered

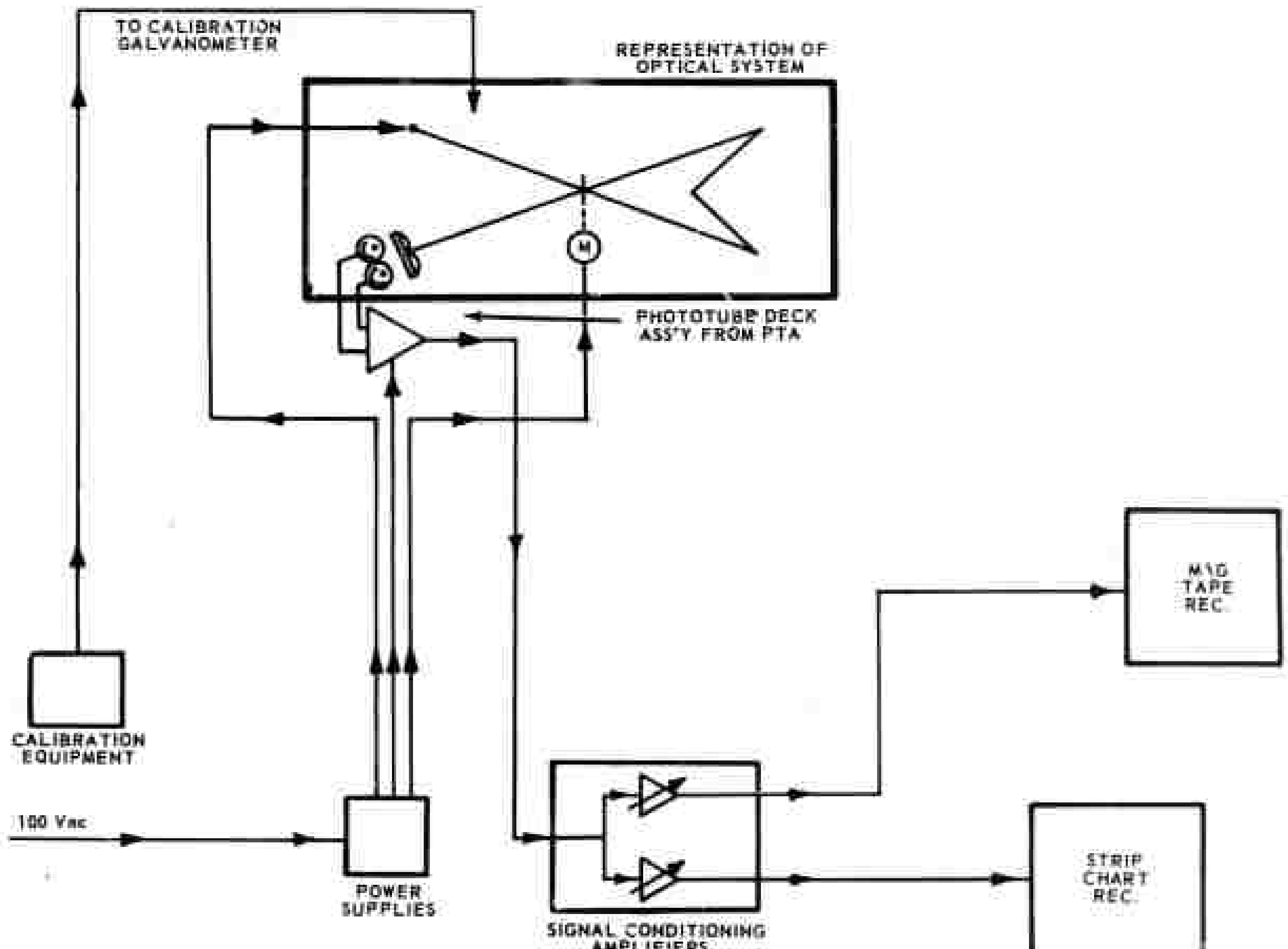

Figure 1. Simplified block diagram for thermal noise study

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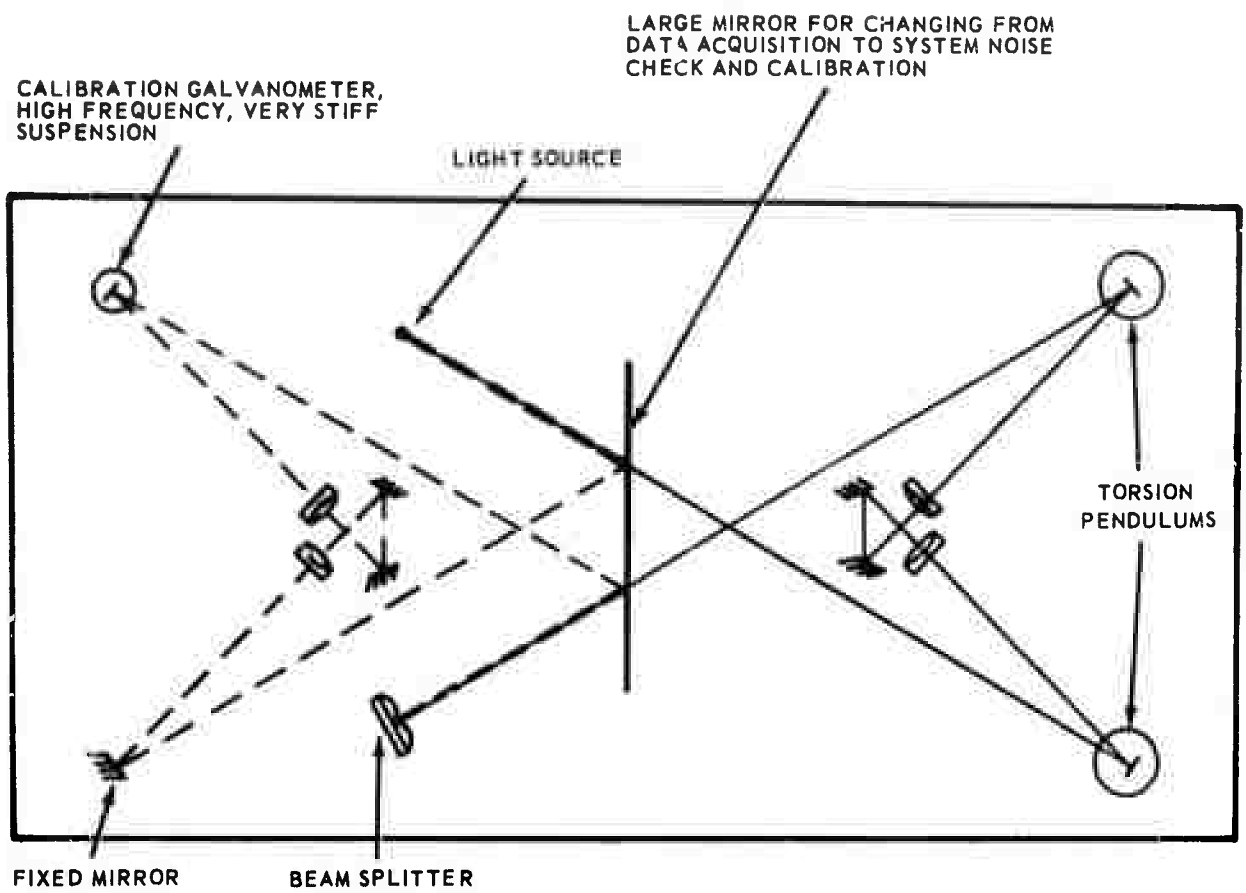

Figure 2. Optical layout

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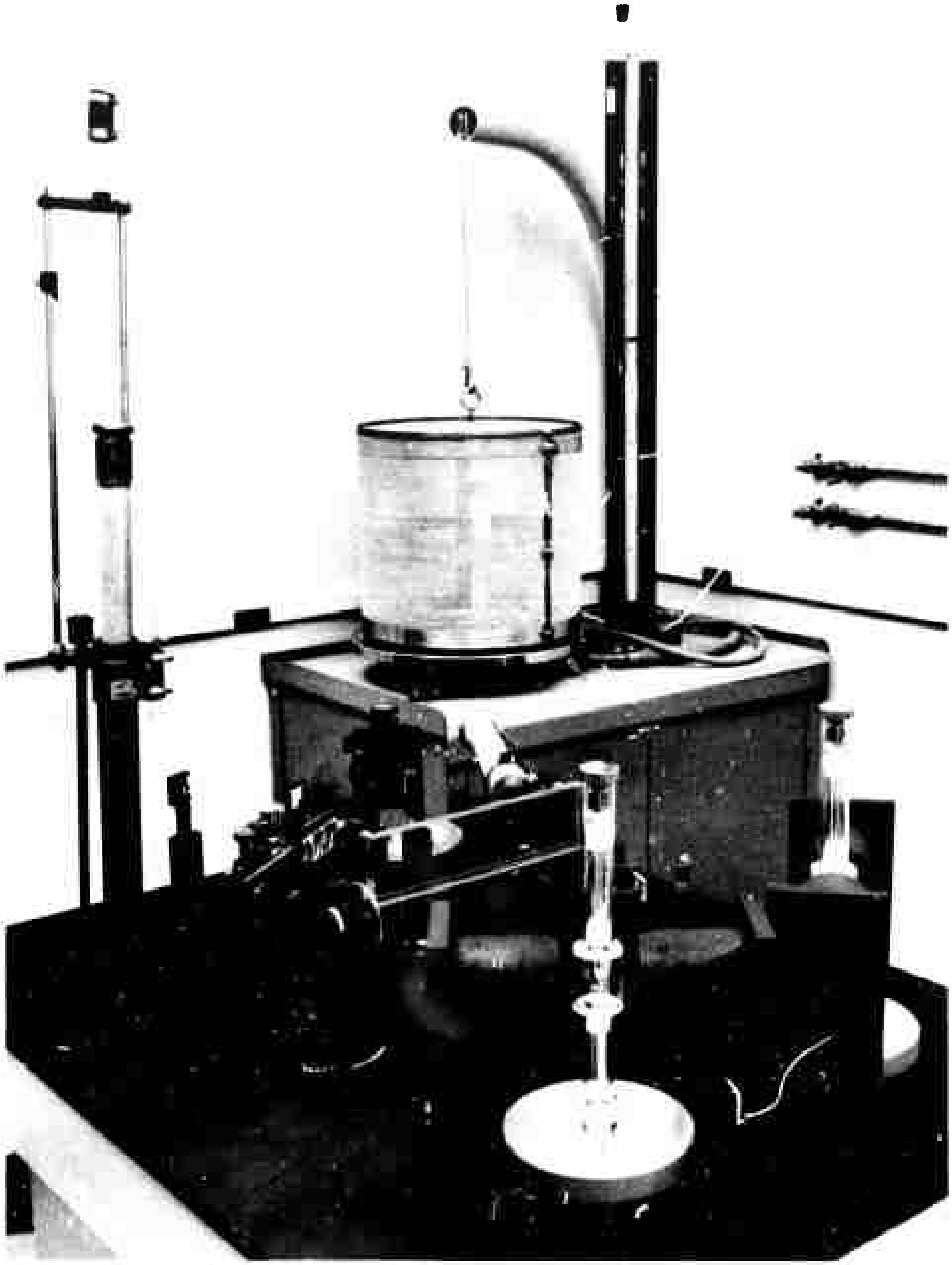

Figure 3. Optical system

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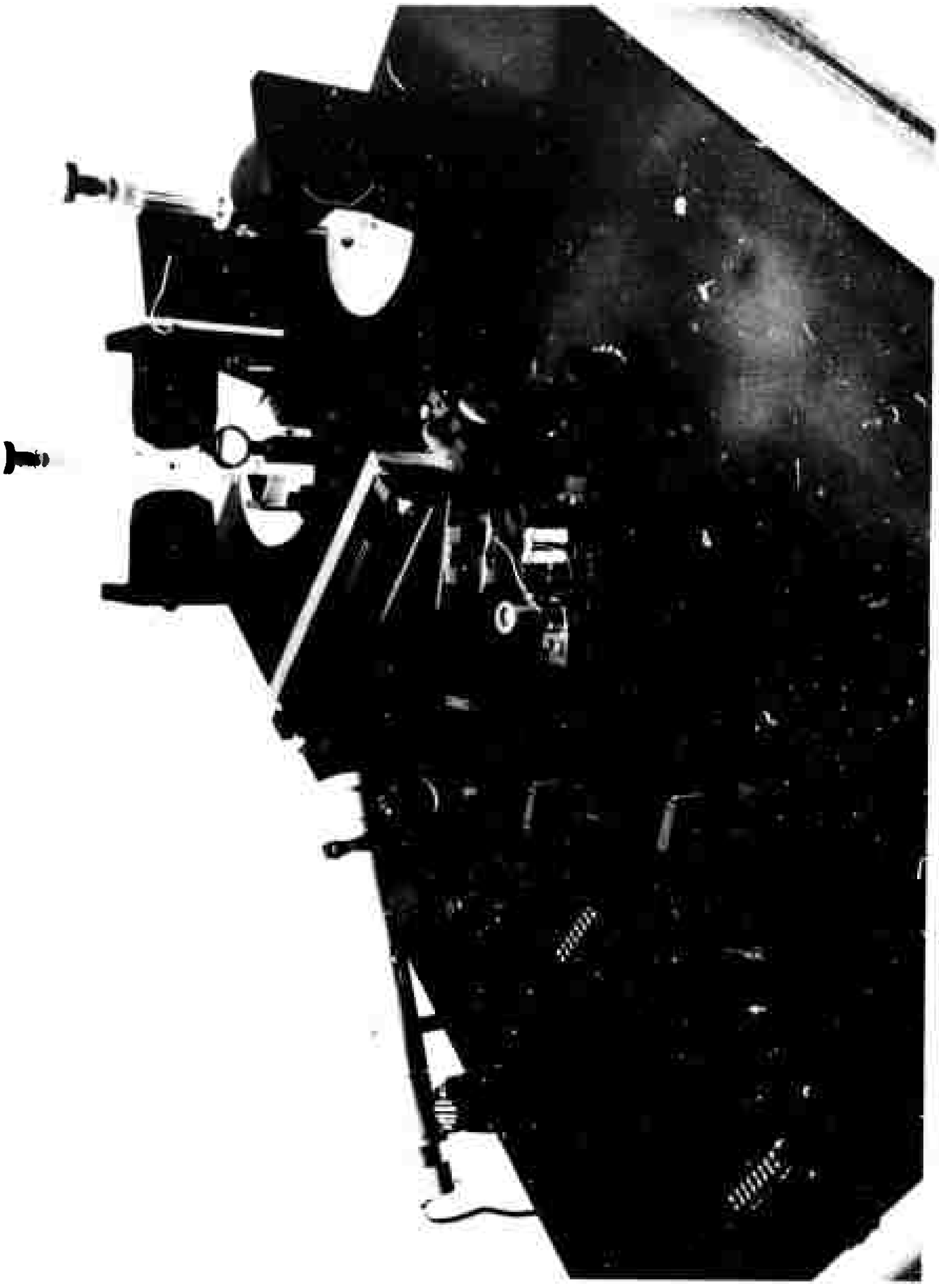

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Figure 4. Close-up view of optical system

in the study so far was that of devising a technique to satisfactorily coat the spheres. Coating of the spheres is presently under way. Upon completion of the coating the pendulums will be reassembled and their natural periods rechecked, prior to completion of the remainder of the work of this task.

The special galvanometer for experiment 2 was designed to match a Harris galvanometer such that the response of the combination would be similar to the response of a typical seismometer-galvanometer combination. The Harris galvanometer represents the seismometer in the combination and the special galvanometer is the galvanometer of the combination. The Harris galvanometer has a natural period of 110 sec and the special galvanometer has a natural period of 10 sec. The armature and suspension for the special galvanometer were completed, mounted in the housing, and checked for natural period and damping.

The magnetic structures for damping the spheres in the torsional pendulums and the special galvanometer were designed and fabricated. These structures were made using magnets from Model 6840 seismometers. Special mountings and pole pieces were made for the magnets. The magnetic structures were charged and the uniformity of the field in each gap is considered very good. The field strengths in the gaps are within 3 percent of each other and each is about 1800 gauss.

3. DEVELOPMENT OF A LONG-PERIOD TRIAXIAL BOREHOLE SEISMOMETER, TASK 1b

3.1 INTRODUCTION

There have been two previous long-period triaxial seismometers designed for the VELA program by the Geotech Division of Teledyne Industries. These seismometers, designated Model 11550 and Model 15560, were completed during the contract period 1 November 1962 to 31 October 1964 under Contract No. AF 33(657)-9967. The present seismometer development is based upon the findings of these two previous designs.

Figure 5 and figure 6 are photographs of the Model 11550 and Model 15560 seismometer, respectively. The Model 11550 is the original concept and is mounted in a 31-inch (0.79 m) diameter Meehanite casting. A sheet metal drum was provided as a cover for the seismometer to protect it from moisture and the disturbing effects of air currents. The physical size of the instrument limited its use to surface or very shallow hole installations.

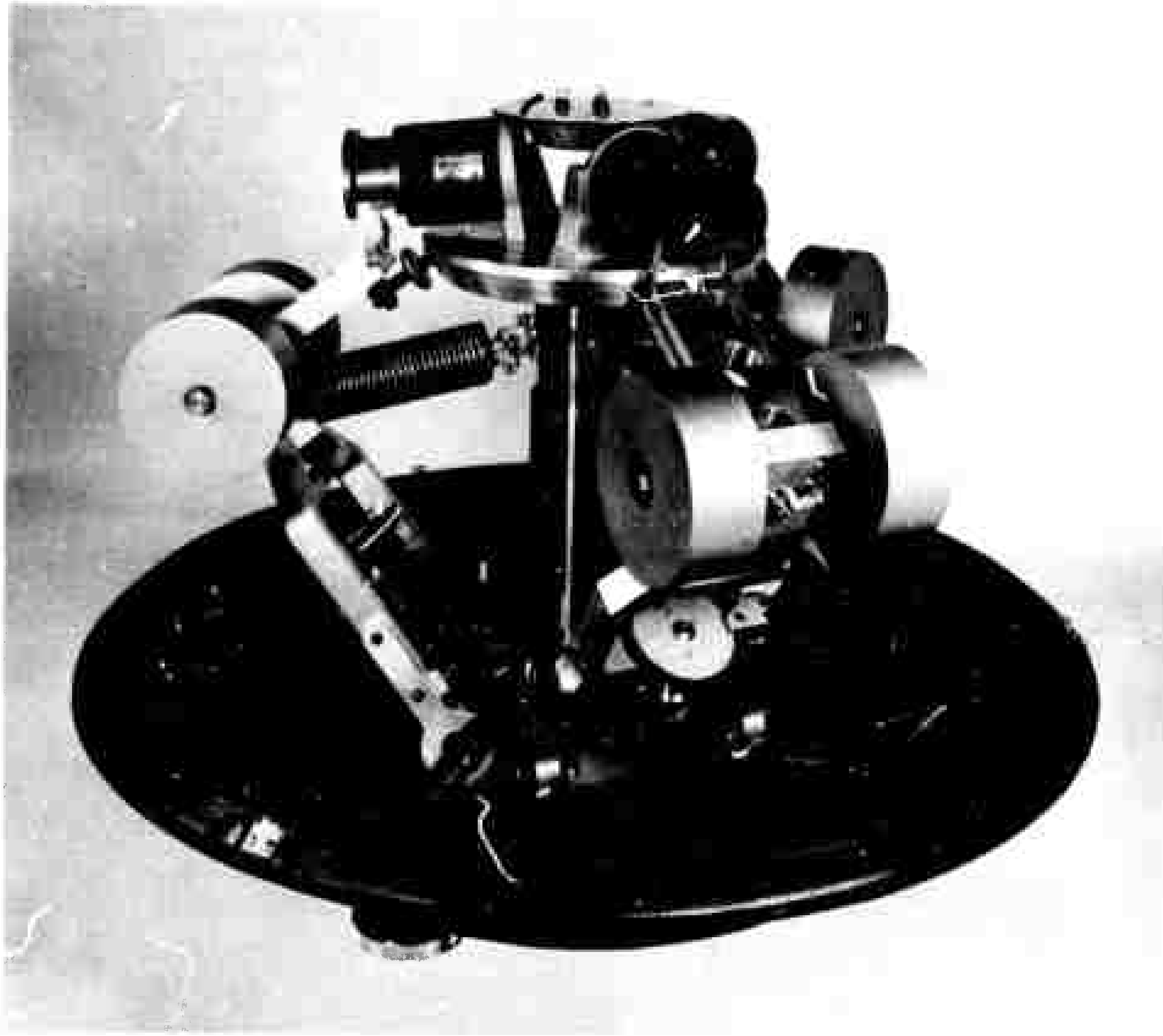

Figure 5. Melton Long-Period Triaxial Seismometer, Model 11550

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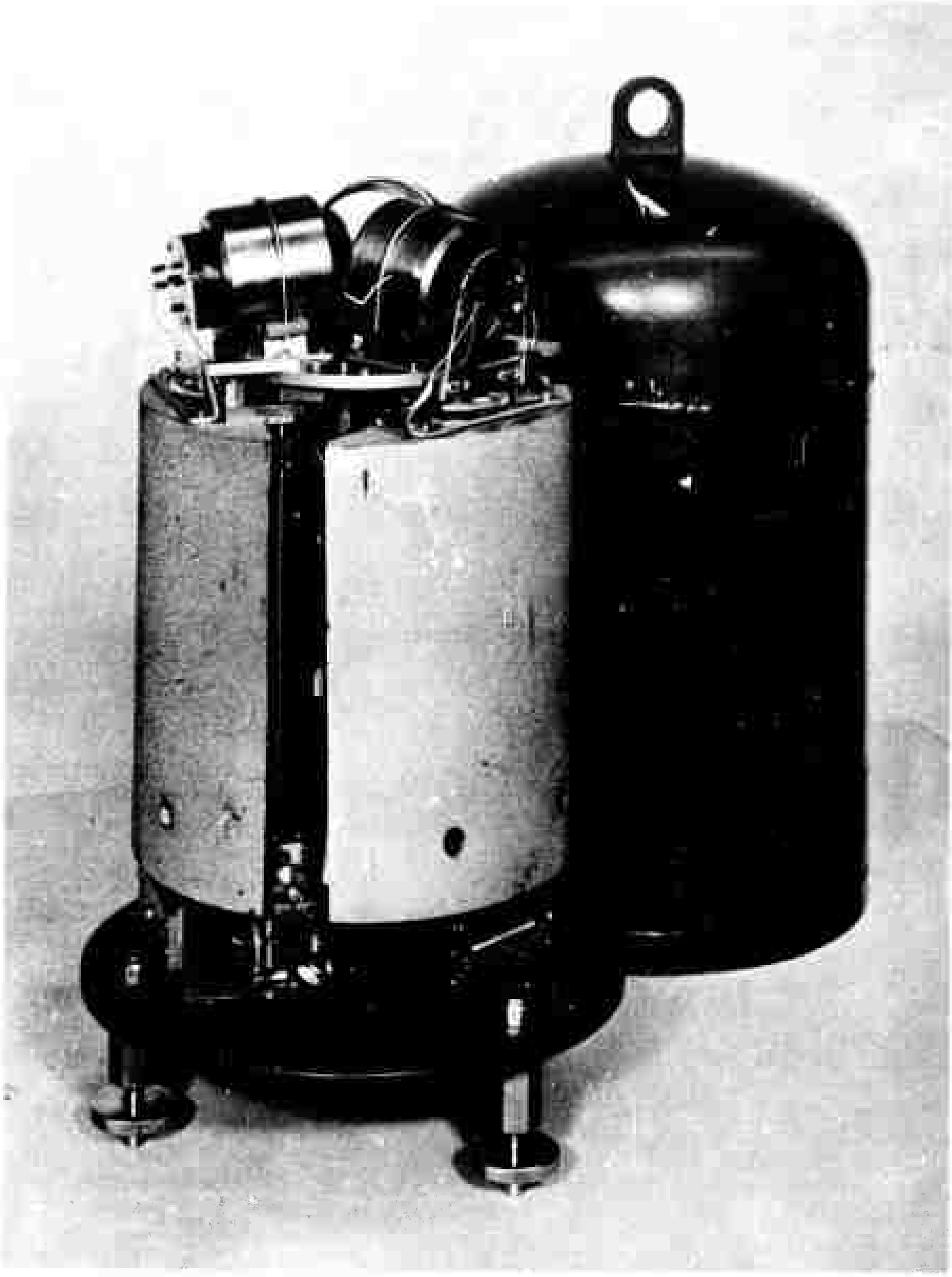

Figure 6. Melton Symmetrical Triaxial Seismometer
Long-Period, Model 15560

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3.2 PROGRESS

The Model 15560 seismometer is a compacted version of the earlier seismometer and was designed to operate in boreholes as deep as 45 meters. Both seismometers have three identical elements clustered around a central column and are identical in principle of operation.

The outside diameter of the Model 15560 seismometer is 12.75 inches (0.32 m). The present development effort contractually requires the seismometer to fit in a 13.375-inch o.d. (12.71-inch i.d.) well casing. It is desirable that it be capable of operating in smaller diameter casings. Since the Model 15560 seismometer is a high-density design, it was impractical to reduce its diameter to that desired. Further, the weight of this instrument is 136 kg (300 lb) and thus is far in excess of the weight that can be conveniently handled by one man.

The two previous long-period triaxial seismometer designs were carefully reviewed before commencing the present design. Model 26310 has been assigned to the present design for reference purposes. This design draws more heavily from the original concept (see figure 5) than from its compacted version (see figure 6).

The Model 26310 seismometer uses unitized construction in which individual units will be assembled together at the site to form the seismometer proper. (See preliminary specifications included as an appendix to this report.) By this method, the seismometer can be transported in pieces of convenient size and weight. There will be three identical seismometer elements, each capable of functioning independently. These elements will be stacked for borehole operation by use of adaptor rings which both orient and interconnect the elements. Auxiliary elements such as the holelocks, are added to the stack in appropriate positions. Each element will contain sufficient through-wiring to accommodate any expected combination of elements stacked below it.

Figure 7 is an outline drawing of the completed seismometer. In the experimental field work to be done in this contract, the seismometer will be lowered into the hole on a string of indexed tubing. This is expected to place it within a few degrees of the desired heading. The tubing string will be disconnected and removed from the hole after the seismometer is in place. In routine field operations the seismometer may be emplaced using only cable to lower it into the hole.

The philosophy being followed in the present design involves the use of the "Ideal" La Coste geometry. This geometry describes a torque balance system in which the force of a spring acting on the mass-support arm exactly

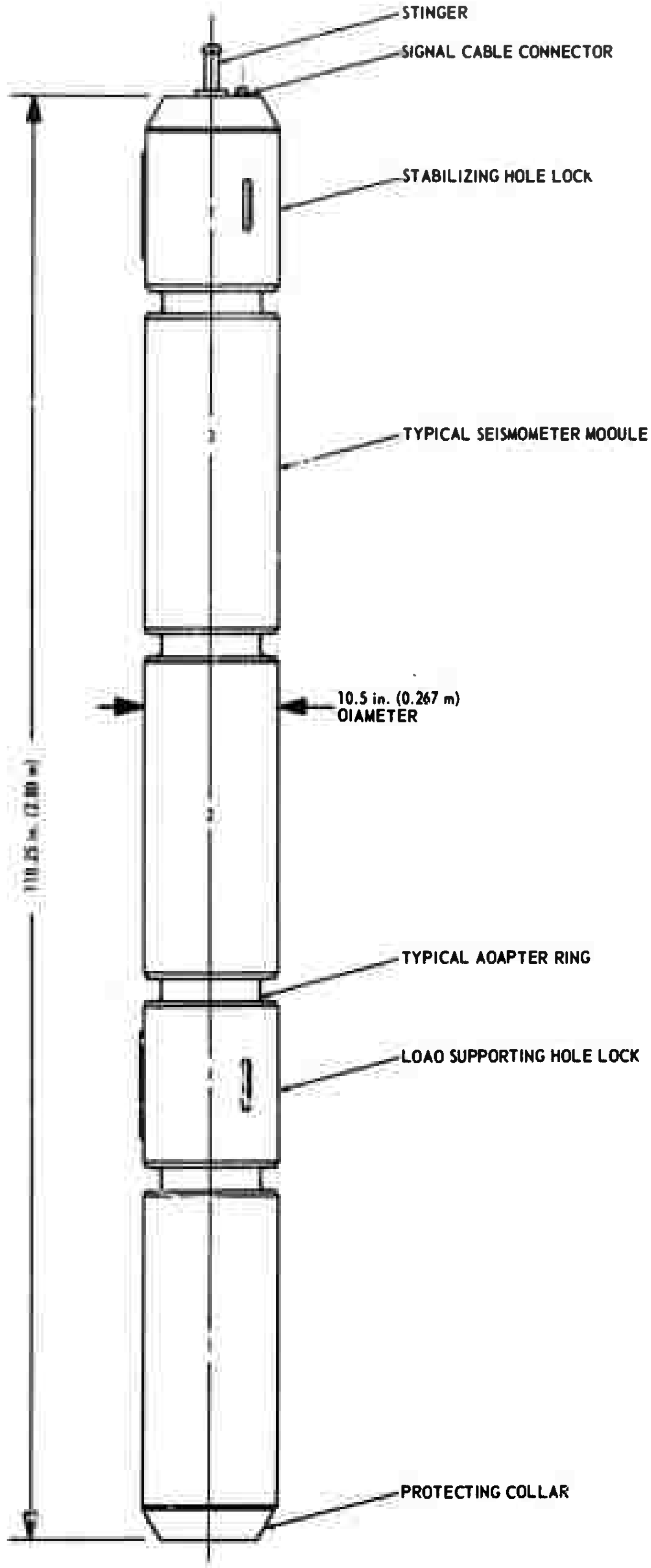

Figure 7. Outline dimensions, Model 26310 long-period triaxial borehole seismometer

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balances the force of gravity acting on the mass. Figure 8 illustrates the arrangement being used. The angle of 35.3° arises from the requirements of symmetry and orthogonality in the triaxial seismometer.

The equation for torque balance of the La Coste geometry is:

$$W r_1 \sin \theta_1 = k r_2^2 \sin \theta_2$$

Gravity torque   Mechanical torque

where W is the force due to the attraction of gravity on the mass M, r_1 is the length of the mass arm, k is the spring rate of the mechanical spring, r_2 is the distance to the mechanical spring attachment points, and θ_1 and θ_2 are the angles the mass arm makes with the vertical and the mast, respectively. In the present design, it is intended that $\theta_1 = \theta_2$ at all positions of the mass as it travels along the arc r_1. Thus, if a "zero" length mechanical spring is used, the two torques, gravity, and mechanical, "track" perfectly and the net restoring force is zero throughout the range, the period is infinite, and the mass will remain in any position it is placed.

This "tracking" of the two opposing torques is essential to the stability of a long-period seismometer. Any deviation from the conditions for infinite period must necessarily result in a nonlinear net restoring force and subsequent instability at long period.

Finite periods can be obtained by altering the ideal La Coste geometry. Such adjustments as tilting the mast slightly from the vertical, moving the spring attachment points, modifing the zero length of the spring, and shifting the mass center-of-gravity are among the means normally used to obtain finite periods. The present design seeks to preserve the ideal La Coste geometry as a mass-support system and to control the free-period by an adjustable auxiliary spring.

An experiment was performed during the present work which involved adjustments to one boom of the Model 11550 seismometer. Adjustments were continued until the ideal La Coste geometry was approached and the mass tended to remain in any position placed, thus approximating the condition for infinite period. At this point, an auxiliary spring was attached to the system. This spring was in the form of a quartz torsion rod and was attached along the axis of the mass-arm pivot. The free length of the quartz rod was adjustable, such that it could be fixed after installation. The free length was initially adjusted to that computed for a 40-second period. A 42-second period was immediately observed. The free length of the rod was subsequently adjusted to that computed for shorter free periods. The expected period was observed in each case.

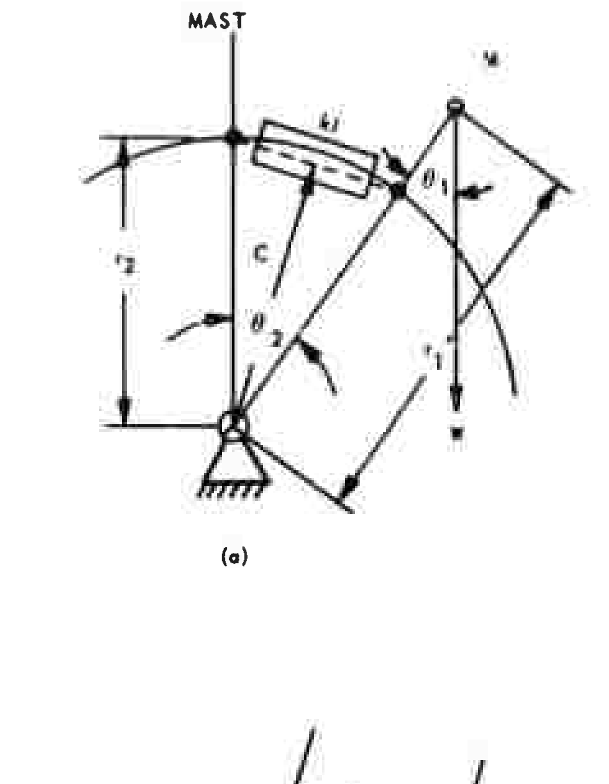

Figure 8. La Coste geometry for Model 26310 seismometer

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Free periods of the order of 25-30 seconds were the longest stable periods previously observed with the Model 11550 seismometer. These periods were obtained by careful adjustment of various parameters such as main spring length and attachment points, instrument tilt, and flexure pivot loading. The ideal La Coste geometry predicts that an infinite period can be obtained. In practice, the approach to an infinite period is seldom observed and the amount of adjustment required to go from periods of 25-30 seconds to an unstable mass postion is exceedingly small.

The success of the above experiment seems to support the concept of maintaining the ideal La Coste geometry as a mass-support system and controlling the period by an auxiliary spring. The present feeling is, that there is a much better chance of achieving a stable long-period instrument in an unattended installation, if each component of the sensitive element is caused to operate as near the ideal as possible. This is not necessarily a new thought, but it does avoid purposely "altering" the ideal geometry in order to obtain finite periods.

Figure 8(b) shows the constants selected for the Model 26310 seismometer. This set of constants is only one of an infinity of possible sets, but they represent a workable compromise which will fit in a 10.5-inch o.d. case. The spring force shown, kl = 16.48 lb, is the force obtained with the mass in its null position and using a zero length spring having a rate of 3.36 lb/inch.

One boom of the Model 11550 has been modified according to the constants shown on figure 8 (b). Figure 9 is a photograph of the modified boom as well as of an original boom. The effective mass of the modified boom is 10.0 kg (22.046 lb) as compared to 13.2 kg (29.1 lb) of the original. The modified boom constitutes the engineering model of a sensitive element of the Model 26310 seismometer. It has been useful in proving the compatibility of the constants selected and is a test-bed for the helical springs, spring calibrator and pivot designs. The modified boom was operated through the range of periods 6-20 seconds. The temperature sensitivity of the system made operation at longer periods difficult. To prove the constants, the geometry of the modified boom was adjusted to exhibit the dimensions and forces shown on figure 8 (b) as closely as possible.

The helical spring used with the modified boom is that originally used on the Model 11550 seismometer. The spring rate and initial tension were altered for use with the engineering model by grinding a calculated amount from the perifery of the helix to form a "D" shaped wire cross section. The spring rate was adjusted to its final value by use of machined calibrators as shown in figure 10. The spring rate was determined by observing the frequency of vibration of a known mass suspended from the spring. Both the spring rate and the zero length of the spring were adjusted to the correct values before installation on the boom.

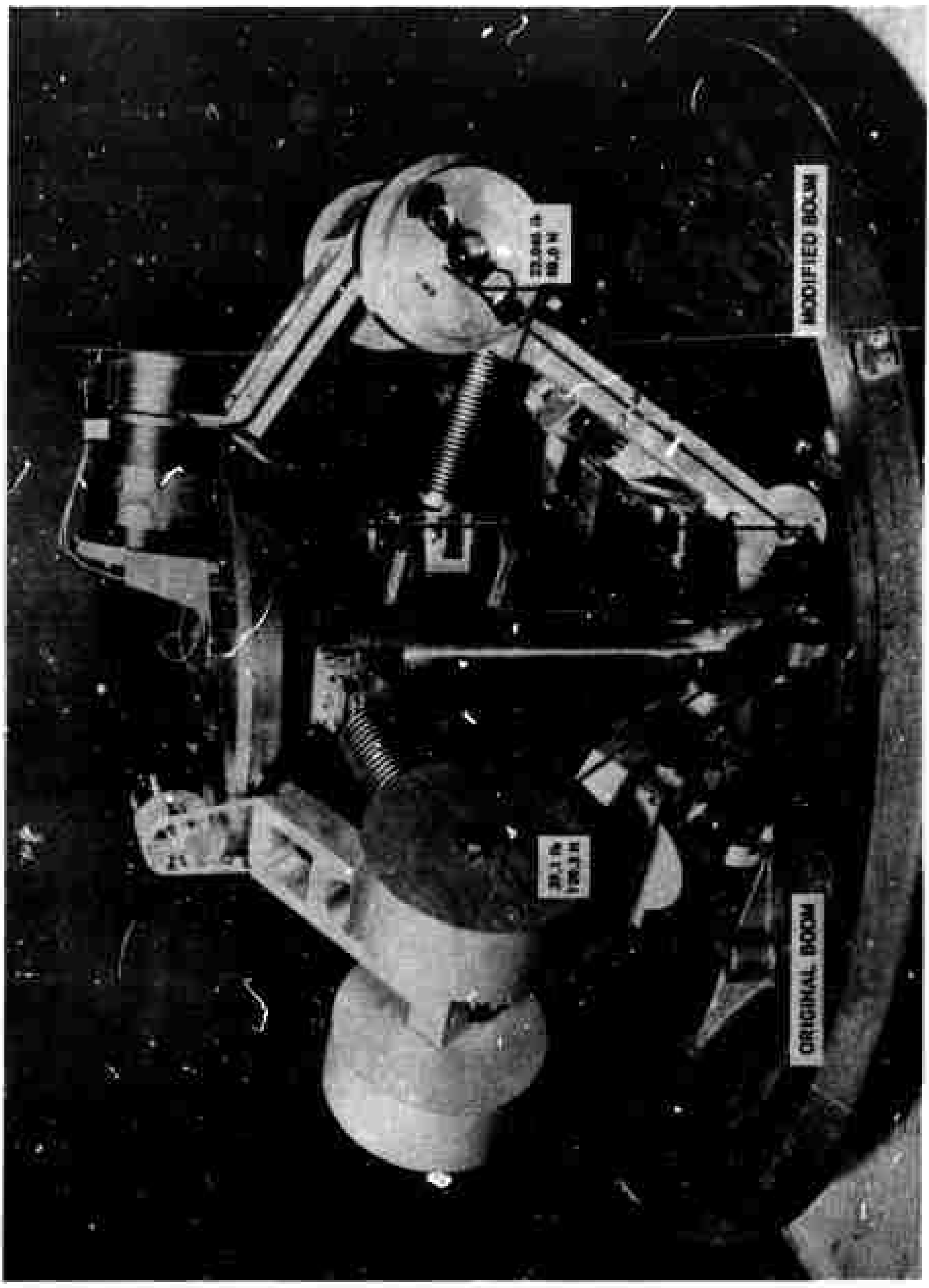

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Figure 9. Model 11550 seismometer with modified boom

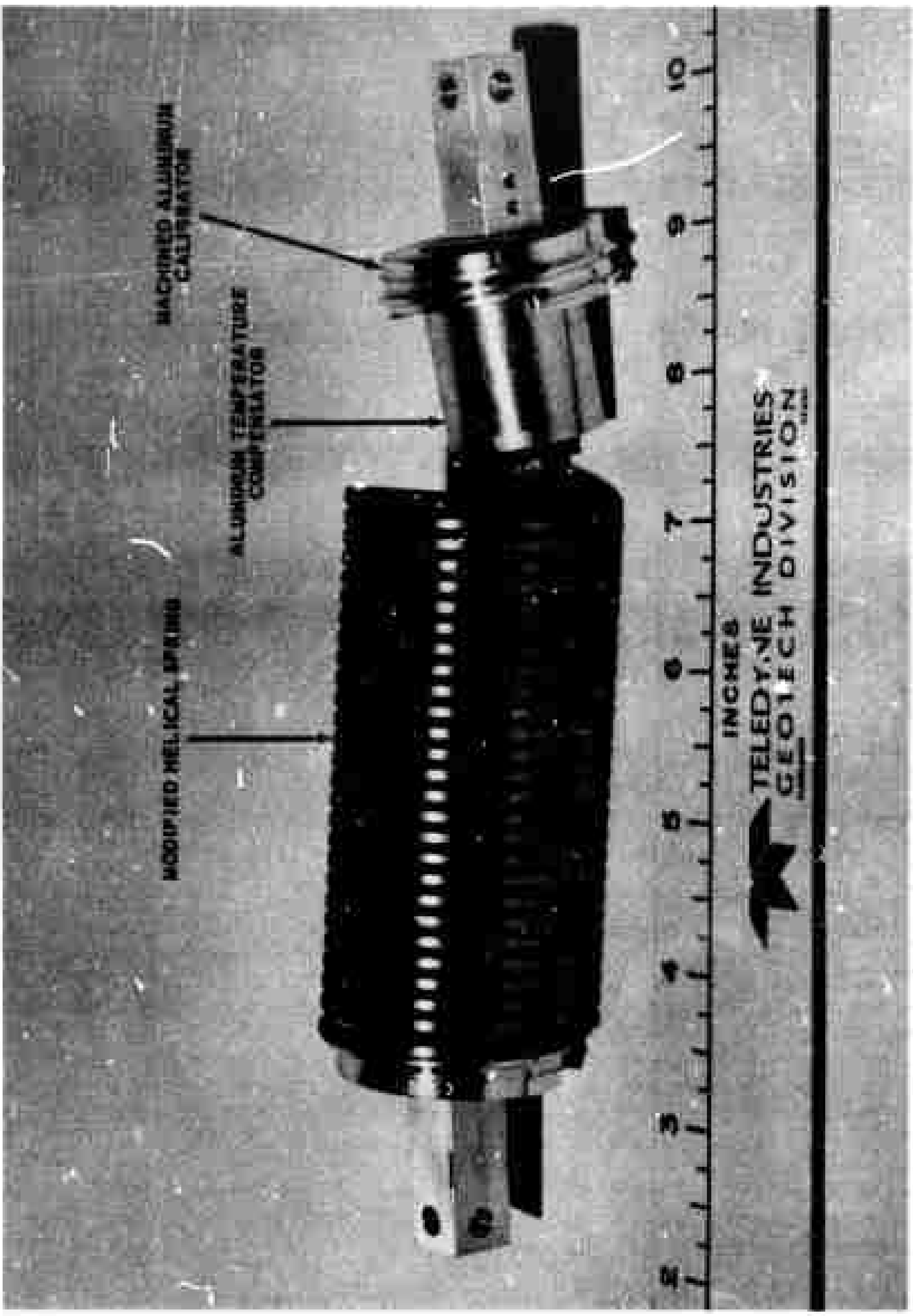

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Figure 10. Model 11550 seismometer helical spring modified by grinding

The specifications for the Iso-Elastic spring designed for the Model 26310 seismometer are included with this report (table 1 and figure 11). This spring is similar to that used in the Model 11550 seismometer in that the spring rate and wire size are approximately the same. The number of turns was reduced and the mean diameter increased from that of the Model 11550, in order to fit the spring in the smaller geometry of the Model 26310. These changes resulted in lower operating stresses and a higher spurious mode frequency.

To compensate for manufacturing variations, machined calibrators will be used to terminate the spring. These calibrators will be used to adjust the spring rate to the exact value required by the geometry and will have the general appearance of those shown in figure 10. The calibrators screw into the spring helix and allow a precise adjustment of the number of active turns.

Instability in l -period seismometers is usually exhibited as mass drift. When the mass drifts against the stops, the seismometer becomes inoperable and an adjustment is then required. Mass drift is due to some modification of the geometry such as would result from changes in the constants due to age, temperature, or orientation versus the vertical. Vertical orientation of the Model 26310 sensitive elements will be controlled by providing integral, motorized tilt tables. These tables will erect the mast to vertical in both planes when the seismometer is in its operating position in the hole.

Aging effects can be artificially accelerated by temperature cycling the completed sensitive element and by applying controlled shock and vibration. Long term creep of such components as the helix spring, will require readjustment of the geometry.

Temperature sensitivity of the long-period seismometer is perhaps the greatest cause of instability. Even though the ultimate environment in which the seismometer is to operate will have a constant temperature, assembly and initial adjustment of the sensitive elements will be made at room temperature. The materials typically used for the mast, the boom-arm, and the helix spring have been Invar, aluminum, and Iso-Elastic, respectively. Iso-Elastic is used as the spring material since it has a low temperature coefficient of the modulus of elasticity. Invar has a nearly zero coefficient of linear expansion versus temperature, while aluminum and Iso-Elastic have relatively large positive coefficients of linear expansion.

Sensitive elements made of the above materials can be adjusted for long periods at a given temperature. As the temperature changes, and since materials of differing coefficients of expansion are normally used, the geometry is altered and the torque-balance relation changes, causing the mass to drift. Mass drift in the Model 11550 seismometer was reduced

Table 1. Specifications, helical spring, Model 26310 long-period triaxial borehole seismometer

Material	Iso-Elastic
Wire diameter	0.140 ±0.001 in. (3.56 mm)
Mean diameter	2.060 in. (0.052 m)
Direction of coil	Right hand
Number of active coils	15.0
Total number of coils	18.0 ±45^{o}
Spring rate	3.36 ±0.17 lb/in. (588 N/m) (based on 15.0 active coils)
Initial tension	12.23 ±1.22 lb (54.40 N)
Working load	16.48 lb (73.30 N) nominal
Solid length	2.660 in. (0.068 m) nominal
Negative length	1.545 in. (0.039 m) (based on 15.0 active coils @ 16.48 lb load)
Spring index $\left(\frac{D}{d}\right)$	14.72
Wahl factor	1.10
Working stress	34,600 psi (2.38 x 10^{8} N/m^{2})
Initial stress	25,700 psi (1.77 x 10^{8} N/m^{2})
Natural frequency of vibration (longitudinal mode)	30.0 Hz approximately (based on 15.0 active coils)

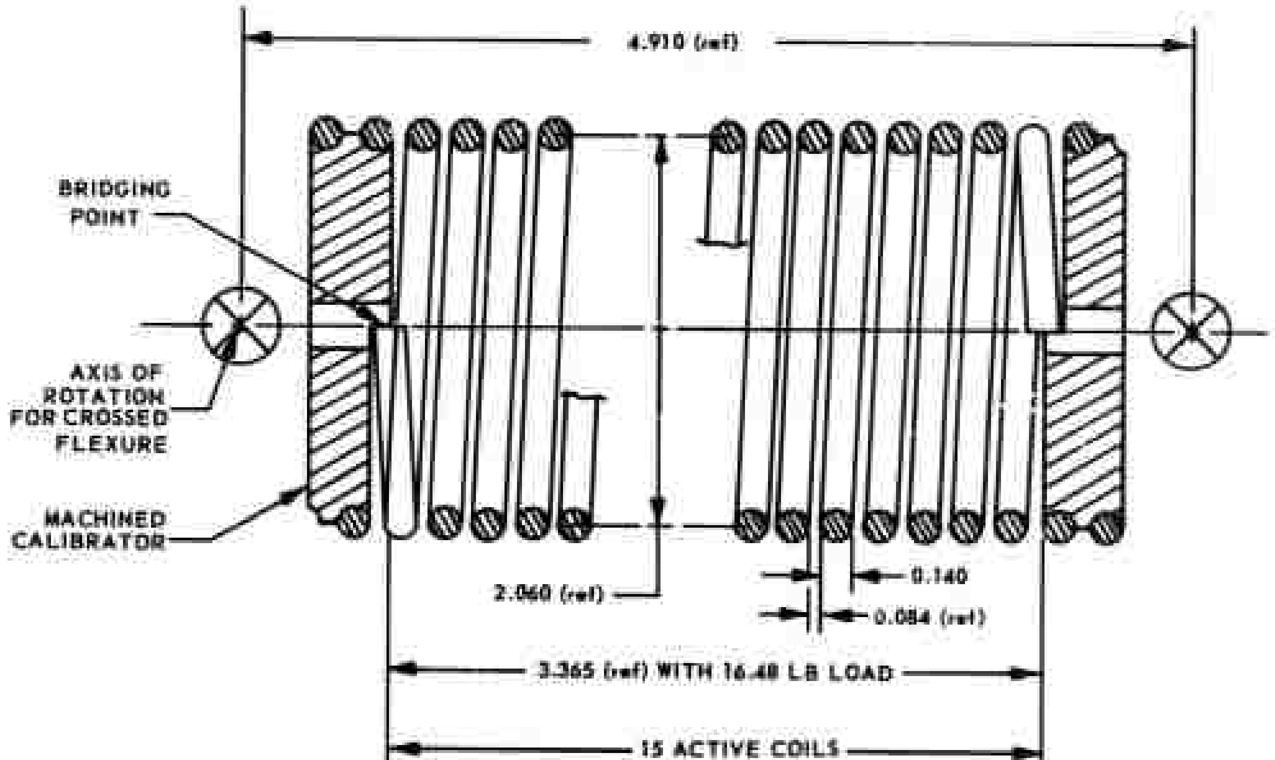

Figure 11. Specifications, helical spring, Model 26310 long-period triaxial borehole seismometer

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by permitting the boom expansion to be partially compensated by helical spring forces. Even so, the mass in this seismometer drifted from stop to stop with a temperature change on the order of 10^{o} centigrade.

The design of the Model 26310 seismometer provides for full temperature compensation of each of the sensitive element components. In this way, the La Coste geometry is most nearly preserved throughout the operating temperature range and thus it is expected that mass drift will be minimized. In the present design, Invar is used for the mast. Since its coefficient of thermal expansion is nearly zero, it will not require compensation and thus becomes the reference component.

The boom-arm must be made of nonmagnetic material which preferably has low density, since it is desirable to concentrate the seismic mass at the end of the boom rather than distribute it along its length. Ordinary nonferrous metals require impractical lengths to achieve a constant length boom versus temperature using a bimetalic arrangement. Quartz, on the other hand, possesses all the desirable qualities required for a temperature compensated boom. Its low coefficient of thermal expansion (0.55×10^{-6} cm/cm/^{o}C) makes it easy to completely compensate by using a short length of aluminum (approx. 21.0×10^{-6} cm/cm/^{o}C) installed as a negative expansion component.

The Iso-Elastic spring, while possessing a nearly zero coefficient of the modulus versus temperature, has a positive coefficient of linear expansion (6.0×10^{-6} cm/cm/^{o}C). Compensating the spring is doubly important since a change in its physical length not only allows a change in the mass position directly, but also changes its zero length, thus altering the geometry. Figure 10 shows the type of temperature compensators that will be used at either end of the helix. These compensators are made of aluminum in the form of a cup. They are mounted so that their expansion subtracts from the expansion of the helix and are dimensioned such that the zero length of the spring is constant over the temperature range. Invar rods are used to connect the cups to the crossed-flexure (see figure 11).

Figure 12 identifies the components of a sensitive element as well as the materials from which they are constructed. Note that an aluminum-molybdenum assembly is used at the mass end of the boom-arm to complete the temperature compensation of the sensitive element. This assembly avoids a permanent attachment to the quartz boom-arm at the spring pivot while maintaining the exact relation the pivot must have with the rest of the geometry. This assembly also provides a resilient attachment to the mass during shipment and installation.

To date, long-period seismometers have been shipped either completely disassembled or with at least the mass removed from the seismometer proper. The shocks encountered in shipment are great enough to seriously

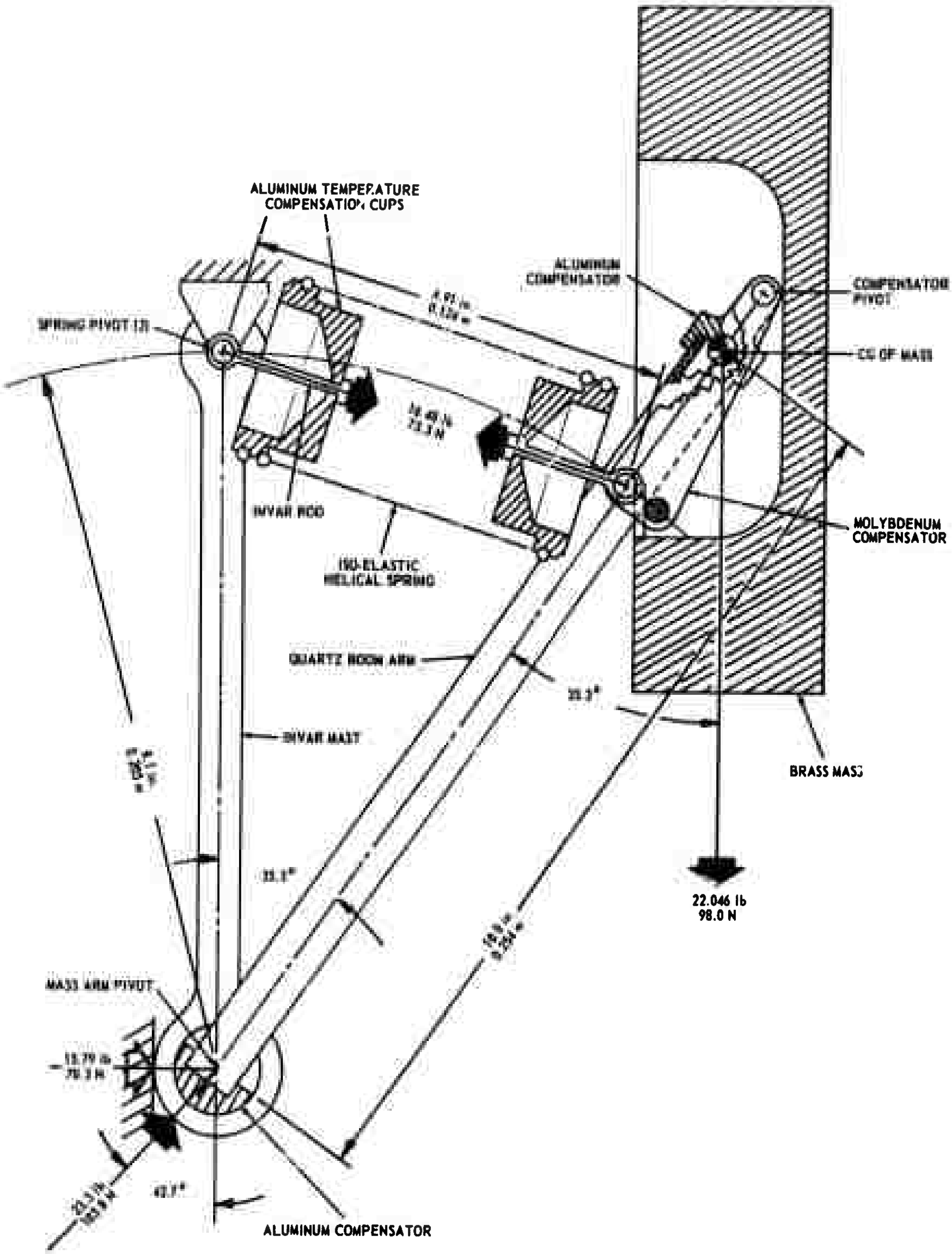

Figure 12. Sensitive element components, Model 26310 long-period triaxial borehole seismometer

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damage the sensitive element components when the mass is left attached to the seismometer boom. At least partial assembly and adjustment of the seismometer at the installation site has been the common practice.

The Model 26310 seismometer is scheduled to be installed in a relatively deep hole. Thus, the shocks experienced by the instrument while in the hole, and as it is lowered into operating position, may exceed those encountered in shipment. Since the seismometer will not be accessible when in the operating position, the instrument will have to be lowered with the mass in place. A design which will sustain the expected installation shocks without damage will also survive similar shocks during shipment.

The present design contemplates an assembly which will be adjusted and sealed after manufacture. Upon arrival at the site, the various elements of the triaxial seismometer will be assembled into a stack and lowered into the hole without removing their covers. The masses will be remotely unlocked and preliminary tests run on each of the elements with the seismometer near the top of the hole. If the seismometer is functioning properly, then the masses will be relocked and the instrument lowered to the operating depth.

Since it is intended that the seismometer elements not be opened after they leave the manufacturer, all the adjustments will have to be made remotely by electric motors installed in the elements. Motors will lock and unlock the mass, adjust the sensitive element tilt in two planes, adjust the mass position and the period. The locking operation, tilt adjustment, and possibly mass position can be automatically sequenced from inside the element. Period adjustment will need to be controlled from the top of the hole.

Figure 13 shows an outline drawing of the present design which will perform all the required functions. The temperature compensated geometry of figure 12 is hung inside an aluminum cage which also provides a mount for the magnetic structure. This assembly is mounted on a two axis tilt-table which is in turn attached to the bottom plate of the sensitive element housing. The mass is locked for shipment by driving two spherical ended jack-screws into sockets provided at the top and the bottom of the mass. The jack-screws are mounted on girders which are in turn attached to the steel rods separating the top and bottom plates of the sensitive element enclosure. When the jack-screws are operated to lock the mass to the frame, the forces resulting from acceleration of the mass, are transferred to the frame rather than to the quartz boom-arm. The mass is resiliently attached to the boom-arm with flexures, so that the relative motion between the locked mass and the arm is absorbed in the flexure.

The aluminum frame, from which the compensated geometry is hung, is also provided with locks for shipment and installation. The method is similar to

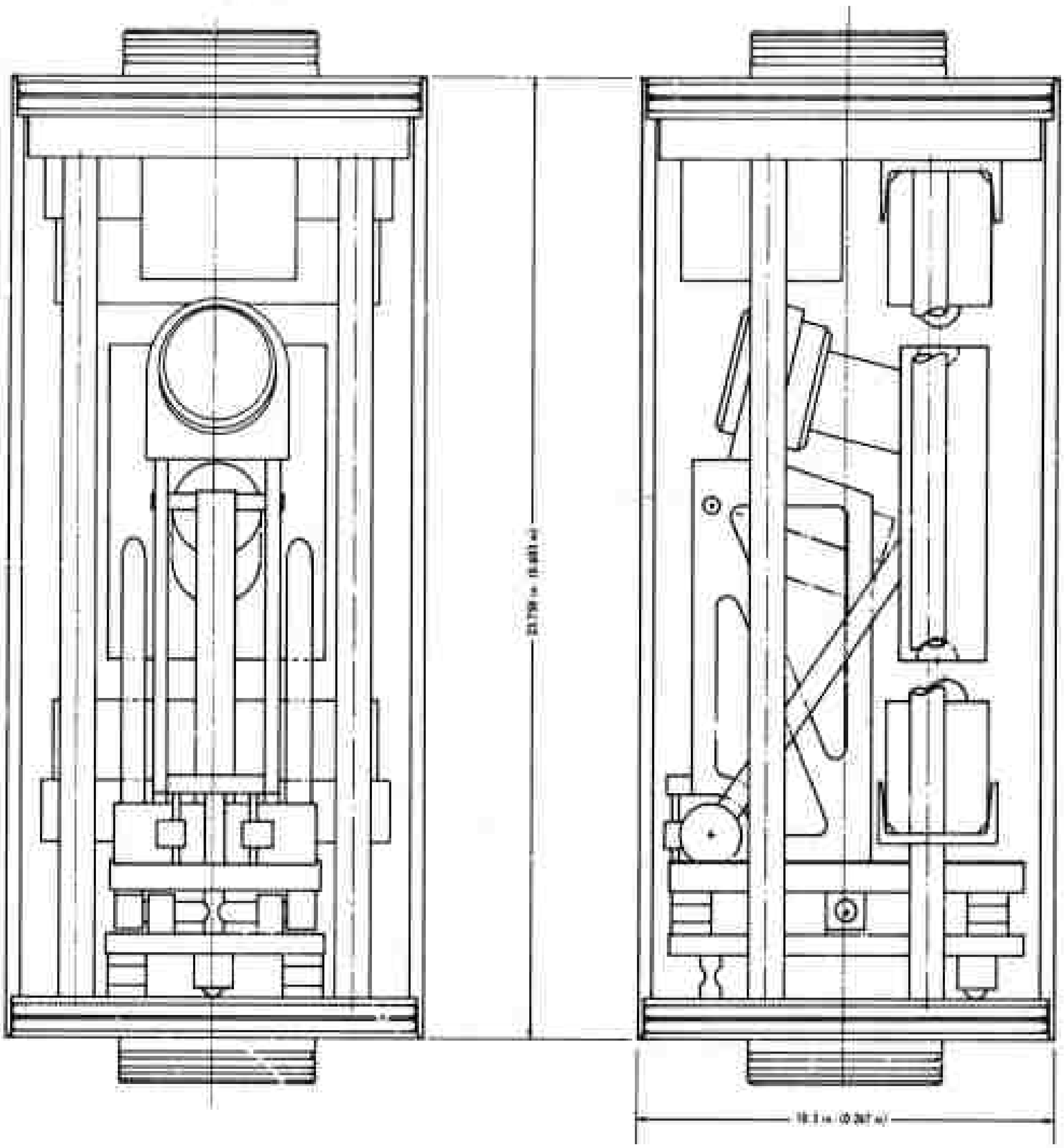


Figure 13. Outline drawing of sensitive element, Model 26310 long-period triaxial borehole seismometer

G 1690

that used to lock the mass, in that the acceleration forces resulting from concentrated masses such as the magnetic structure, are transferred to the enclosure frame. In this way, the quartz boom-arm and the flexure pivots are not required to sustain the exaggerated forces generated during shipment and installation.

The preliminary specifications for the Model 26310 long-period triaxial borehole seismometer are included as an appendix to this report. The weights given were a best estimate as of the date of the specification. Subsequent design work has allowed significant weight reduction of the seismometer module and thus the weight of the complete seismometer.

APPENDIX 1 to TECHNICAL REPORT NO. 66-94

STATEMENT OF WORK TO BE DONE

EXHIBIT "A"

STATEMENT OF WORK TO BE DONE

AFTAC Project Authorization No. VELA T/6706

1 - MAR 1966

1. Tasks:

a. Experimental Investigation of Thermal Noise. Continue the experimental investigation, defined in Project VT/072, of thermal noise components in seismograph systems, using torsional pendulums and associated equipment available from that project. Determine experimentally the spectral distributions of thermal noise in seismograph systems and compare the experimental results with theoretical predictions, as those derived by the National Bureau of Standards, for example. Provide data and methods for determining the ultimate possible magnification of a seismograph. Work on this task is to be completed within 4 months of the initial authorization date.

b. Development of a Long-Period Triaxial Borehole Seismometer. Modify the "Melton" long-period triaxial seismometer developed under Project VT/072 to adapt it for routine operation in shallow (200-foot) boreholes. Reduce the seismometer's diameter so it will fit inside standard 13.375-inch outside diameter shallow-well casing. Develop and add a suitable level sensor and remotely-controlled levelling device.

c. Preliminary Testing of the Long-Period Triaxial Borehole Seismometer. Prepare a cased, shallow borehole at a VELA seismological observatory to be designated by the AFTAC project officer. Assemble handling equipment for installing the seismometer. Conduct preliminary tests of the modified instrument in the test hole to determine its stability and the effects of temperature and local tilting as functions of depth. Through the use of improved installation techniques, selective filtering, design improvement or other means, develop a method for operating the seismometer so that magnification in the 10 to 100 sec period band is limited only by propagating seismic noise.

d. Field Measurements with the Long-Period Triaxial Borehole Seismometer. Collect and analyze data to determine long-period signal and noise characteristics in shallow boreholes, to identify principal long-period seismic noise components, to ascertain depth-environmental effects, and to compare the performance of the triaxial borehole seismometer with standard long-period seismometers.

2. Data Requirements: Provide report as specified by DD Form 1423, with Attachment 1 thereto.

AF 33(657)-16406

Attachment 1 to DD Form 1423
REPORTS
AFTAC Project Authorization No. VELA T/6706

1. General: Provide monthly, quarterly, final, and special reports in accordance with sentence 1, paragraph 1 of Data Item S-17-12.0, AFSCM 310-1; however, if that data item conflicts with the instructions of paragraph 2 below, the latter will take precedence.

2. Reports:

a. Monthly Status Reports. A monthly letter-type status report in 16 copies, summarizing work for the calendar month, will be submitted to AFTAC by the 5th day of the following month. Each report will be identified by the data listed in paragraph 2e and will include, but not be limited to, the following subject areas:

(1) Technical Status. Include accomplishments, problems encountered, future plans, actions required by the government, and appropriate illustrations and photographs.

(2) Financial Status. The contractor will follow the provisions of Data Item A-15-17.0, AFSCM 310-1A (Cost Planning and Appraisal Unit), in submitting financial data.

For the last month of each report period covered by a quarterly progress report, the monthly status report need include only the financial information.

b. Quarterly Progress Reports. Quarterly progress reports in 50 copies, summarizing work for 3-month periods, will be submitted to AFTAC within 15 days after the close of each such period. Each report will be identified by the data listed in paragraph 2e and will include the notices listed in paragraph 2f. Each report will present a precise and factual discussion of the technical findings and accomplishments for the entire report period, using a format similar to that of the final reports under Contract AF 33(657)-9967, as well as the technical information ordinarily required in the monthly reports.

c. Final Reports. The final report on Task 1a will be submitted in 50 copies to AFTAC within 60 days after work on that project is completed; the final report on the remaining tasks will be submitted in 50 copies within 60 days after the completion of all work. Each report will be identified by the data listed in paragraph 2e and will include the notices listed in paragraph 2f. Each report will present a complete and factual discussion of the technical findings and accomplishments of the project tasks, using the quarterly-report format.

d. Special Reports.

(1) Special reports of major events will be forwarded by telephone, telegraph, or separate letter as they occur and should be included in the

following monthly report. Specific items are to include, but are not restricted to program delays, program breakthroughs, and changes in funding requirements.

(2) Special technical reports may be required for instrument evaluations, project recommendations, and special studies when it is more desirable to have these items reported separately from the quarterly or final reports. Specific format, content, number of copies, and due dates will be furnished by this headquarters.

(3) All seismograms and operating logs, including pertinent information concerning time, date, type of instruments, magnification, etc., will be provided when requested by the AFTAC project officer.

e. Identification Data. All monthly, quarterly, and final reports will be identified by the following data:

AFTAC Project No. VELA T/6706.

Project Title.

ARPA Order No. 624.

ARPA Program Code No. 6F10.

Name of Contractor.

Contract Number.

Effective Date of Contract.

Amount of Contract.

Name and phone number of Project Manager, Scientist, or Engineer.

f. Notices.

(1) All quarterly and final reports will include the following notices on the cover and first page or title page:

Sponsored by
Advanced Research Projects Agency
Nuclear Test Detection Office
ARPA Order No. 624

Qualified users may request copies of this document from:

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22341

This research was supported by the Advanced Research Projects Agency, Nuclear Test Detection Office, under the VELA-UNIFORM Program and was accomplished under the technical direction of the Air Force Technical Applications Center under contract AF 33(657)-16406.

(2) All quarterly and final reports will include a copy of DD Form 1473, Document Control Data - R&D (Reference AFR 80-29). AFTAC will designate the appropriate Availability/Limitations Notice for use on these forms.

3

APPENDIX 2 to TECHNICAL REPORT NO. 66-94

GEOTECH PRELIMINARY SPECIFICATIONS
LONG-PERIOD TRIAXIAL BOREHOLE SEISMOMETER, MODEL 26310

PS-26310
7 July 1966

GEOTECH PRELIMINARY SPECIFICATIONS

LONG-PERIOD TRIAXIAL BOREHOLE SEISMOMETER, MODEL 26310

PURPOSE

This seismometer is designed to detect long-period signals in the 0.1-0.01 Hz range. Its construction allows it to be operated at a depth of 100 m or less below the earth's surface.

The seismometer consists of three identical modules each 0.267 m (10.5 in.) diameter stacked vertically, holelocks to engage at casing collars, provisions for electrical connection, and provisions for electrical lead switching. The modules are oriented with respect to each other by guide pins. The sensitive axes of the seismometer modules are inclined 35° 16' from horizontal and are 120° apart in azimuth.

The seismometer is lowered to the desired depth by a string of tubing. The tubing is detached after placement of the instrument.

OPERATING CHARACTERISTICS

Each seismometer module:

Natural period	10-25 sec (remotely adjustable)
Weight of inertial mass	10 kg (22 lb)
Mass lock	Remotely operated
Mass position	Remotely operated
Mass travel	±5 mm min
Data coil resistance	550 Ω ±10% at 25°C
Average flux	0.2 Wb/m^2
Critical damping resistance	1700 Ω ±10% at 25 sec period
Internal damping	Less than 10% of critical
Calibration provisions	Electromagnetic
First spurious mode	Above 10 Hz

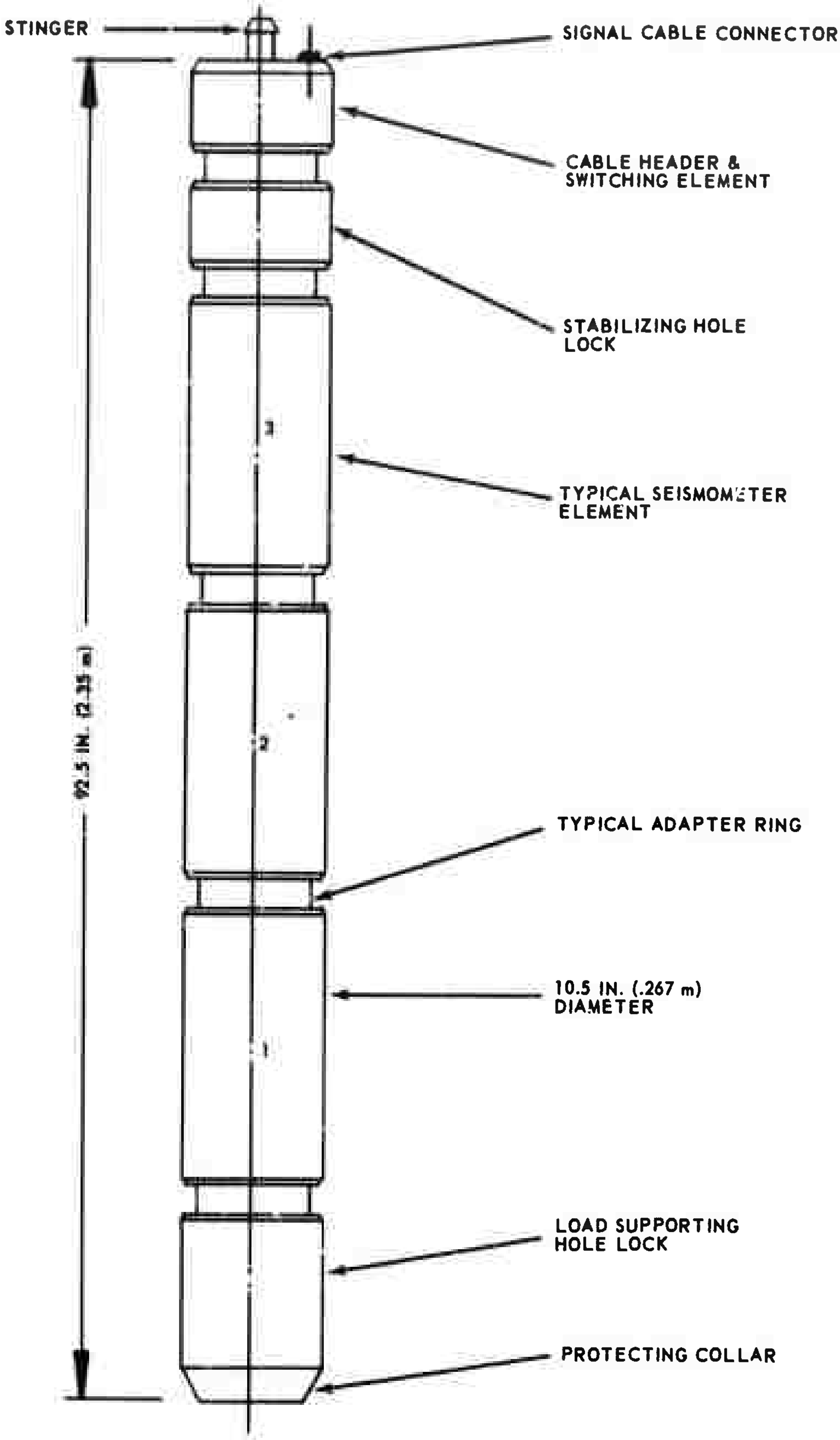
POWER REQUIREMENTS	(Voltages to be determined)
Seismometer	None
Holelock	3 W max.
Switch unit	3 W max.
Centering motor	3 W max.
Mass lock	3 W max.
Mass position monitor	1 W max.
PHYSICAL CHARACTERISTICS	
Each seismometer module:	
Diameter	0.267 m (10.5 in.) max.
Length	0.47 m (18.5 in.)
Weight	72.6 kg (160 lb) max.
Complete seismometer	
Diameter	0.267 m (10.5 in.) max.
Length	2.35 m (92.5 in.)
Weight	386 kg (850 lb) max.
Holelock	
Operating diameter	0.279 to 0.340 m (11 to 13-3/8 in.)
ENVIRONMENTAL CHARACTERISTICS	
Operating temperature	-2 to 60°C (+30 to 140°F)
Storage temperature	-51 to 85°C (-60 to 185°F)
Operating pressure	2.07×10^6 N/m^2 (300 psig)
Static test pressure	3.44×10^6 N/m^2 (500 psig)

ENVIRONMENTAL CHARACTERISTICS (Continued)

Tilt	Adjustable for operation up to 5^{c} from vertical
Shock	Will meet DSE-4
Vibration	Will meet DSE-4
Corrosion resistance	Capable of 2 yr min exposure to all soil acids or salt water

CONNECTORS

Undetermined


STINGER
SIGNAL CABLE CONNECTOR
CABLE HEADER & SWITCHING ELEMENT
STABILIZING HOLE LOCK
TYPICAL SEISMOMETER ELEMENT
92.5 IN. (2.35 m)
3
2
1
TYPICAL ADAPTER RING
10.5 IN. (.267 m) DIAMETER
LOAD SUPPORTING HOLE LOCK
PROTECTING COLLAR

G 1212

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Teledyne Industries, Geotech Division 3401 Shiloh Road, Garland, Texas	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Quarterly Report No. 1, Project VT/6706
LONG-PERIOD SEISMOGRAPH DEVELOPMENT

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Quarterly Report, 1 July through 31 September 1966

5. AUTHOR(S) *(Last name, first name, initial)*

Shappee, Richard M.
Kirkpatrick, Burnard M.
Wayne Trott

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
25 October 1966	40	8

8a. CONTRACT OR GRANT NO. AF 33(657)-16406 b. PROJECT NO. VELA VT/6706 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 66-94 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Equipment was designed to test the validity of seismograph thermal noise theories. (U)

A long-period triaxial borehole seismometer using "La Coste" geometry was designed. (U)

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Thermal noise Long-period borehole seismometer VT/6706						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

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8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

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If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.