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TECHNICAL REPORT NO. 68-44

DEVELOPMENT OF LP WAVE DISCRIMINATION CAPABILITY USING LP STRAIN INSTRUMENTS

Quarterly Report No. 1, Project VT/8706

GEOTECH

A TELEDYNE COMPANY

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Quarterly Report No. 1, Project VT/8706

by

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31 October 1968

IDENTIFICATION

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ABSTRACT

The design of strain seismographs capable of detecting long-period seismic motion is in progress. The moving coil-permanent magnet and the direct current-variable capacitance techniques appear to be the most promising and laboratory models of transducers using these techniques are being constructed for testing. Many mines in the Payson, Arizona, and the Las Cruces, New Mexico, areas have been visited. Three mines meeting many of the requirements for instrument installation were located and could be used if necessary improvements are made.

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DEVELOPMENT OF LP WAVE DISCRIMINATION
CAPABILITY USING LP STRAIN INSTRUMENTS
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1. INTRODUCTION

This report discusses the progress during July, August, and September 1968, in designing vertical and horizontal long-period (LP) strain seismographs with gain and response characteristics equivalent to those of the advanced LP inertial instruments. The designed instruments are to be used in conjunction with inertial seismographs to develop techniques for discrimination of LP seismic waves. The major effort on each task of the statement of work is discussed in separate sections. This report is to apprise the Project Office of the current status of project VELA T/8706. It is submitted in compliance with Sequence No. A004 of the Contract Data Requirements List, Contract F33657-69-C-0121.

2. DEVELOP DESIGN SPECIFICATIONS, TASK a(1)

The preliminary design specifications for vertical and horizontal LP strain seismographs presented in Technical Proposal No. P-1254 have been reviewed. These specifications are adequate for the initial investigation and will be used until the final specifications are prepared. Because of the ability of strain instruments to sense long-period signals, the design will include two signal outputs for each seismograph component. The first signal output will match the frequency response of the Advanced Long-Period (inertial) System (ALPS) for detection of seismic waves with periods between 10 and 100 seconds. The second signal output will enhance seismic waves with ultra long-periods (ULP) between 100 and 1000 seconds.

2.1 ADVANCED LP INERTIAL SYSTEM (ALPS) OUTPUT

The primary signal output from the strain seismograph will have an amplitude and phase response similar to the present ALPS low gain channel. Although this response does not have a notch filter to reduce 6-second period microseisms, operation in the mid-continent of the United States at the high magnifications desired will be possible due to the low level of 6-second microseismic activity.

The interaction between the seismometer and the galvanometer due to the close coupling in the ALPS is a factor that is being considered in the strain system design. Figure 1 shows the difference in phase response between a closely coupled inertial seismometer-galvanometer system (coupling coefficient, α, of 0.823) as in the ALPS and an equivalent loosely coupled system (α = 0.003) with the same seismometer-galvanometer parameters. Figure 2 is the amplitude response of these two systems. The theoretical curves in figures 1 and 2 were generated

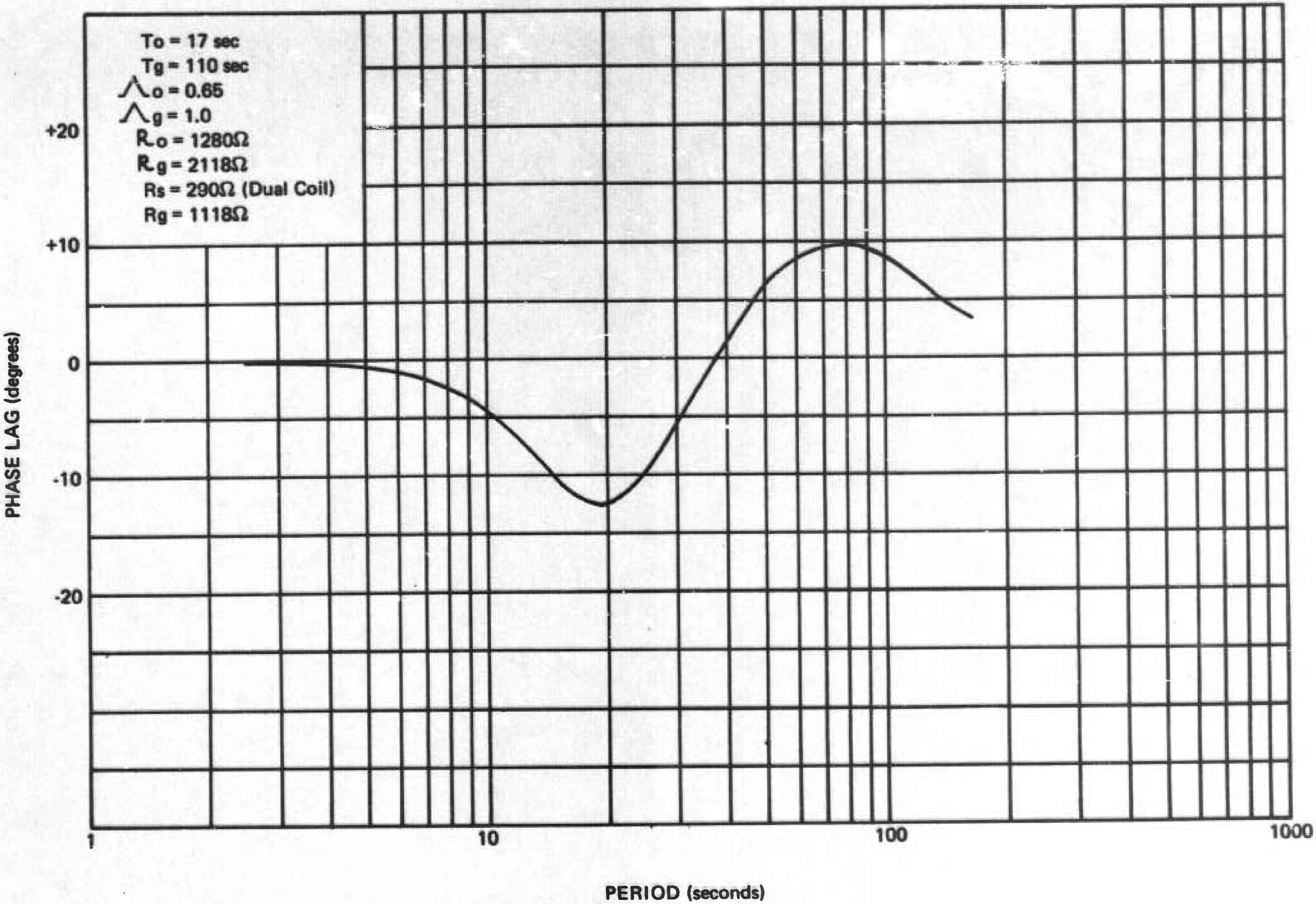

Figure 1. Difference in phase response in the advanced LP inertial low gain seismograph response caused by changing coupling (α) from a low value (0.003) to a high value (0.823)

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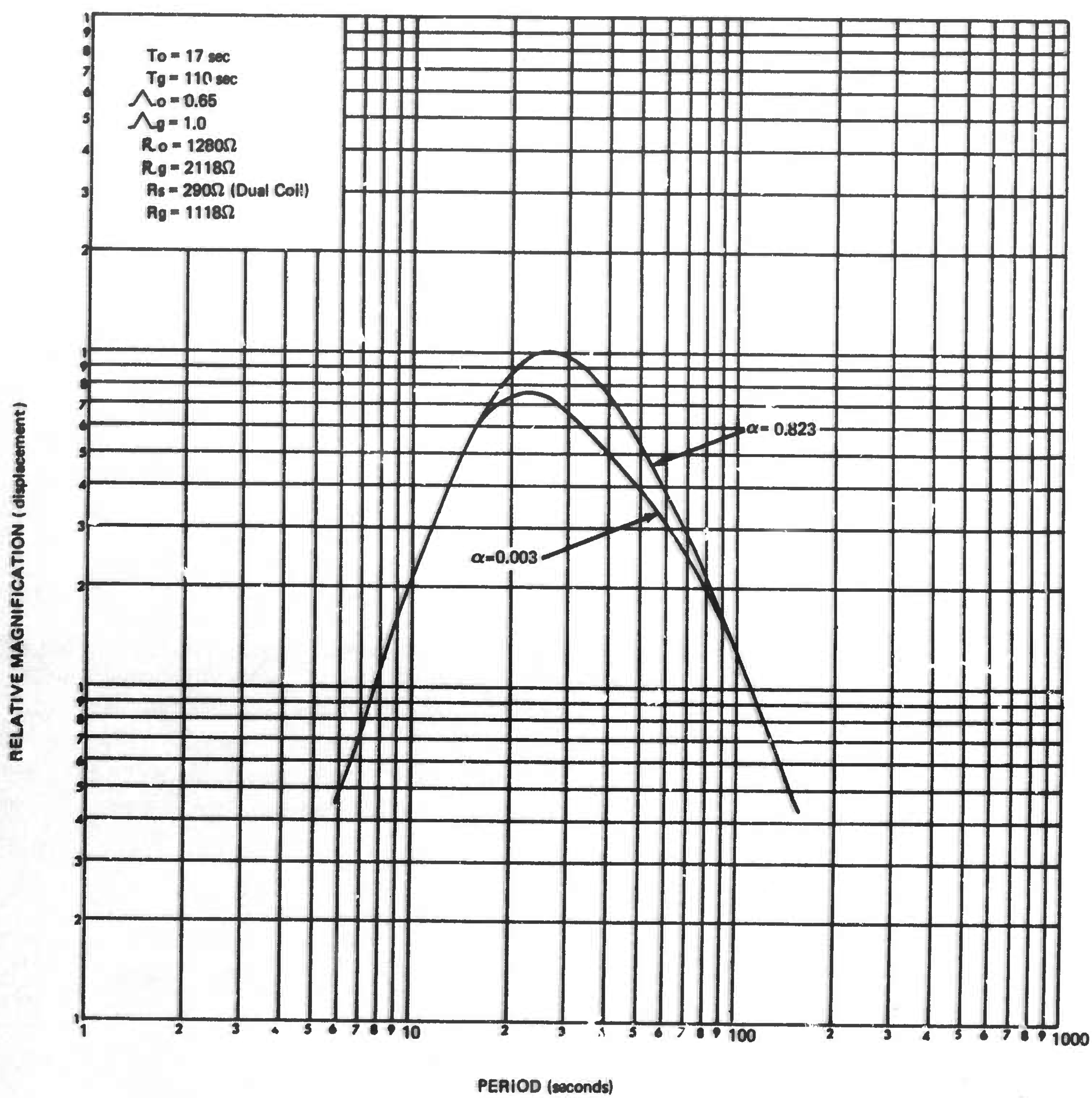

Figure 2. Amplitude response of the advanced LP inertial low gain seismograph under two conditions of seismometer to galvanometer coupling (α)

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by computer programs which use equations given by Johnson and Matheson (1962). The strain channels will not be affected by coupling because solid state amplifiers will be used thereby eliminating the galvanometers. The strain channels will have an amplitude and phase response similar to the loosely coupled inertial channels.

If the strain and the inertial system responses are to be equivalent, some method of compensating for the phase differences must be provided. Several methods are possible. First, the coupling of the inertial system may be reduced with a corresponding reduction in gain of about 20 dB. Second, a complex compensating filter can be designed. Third, the parameters of the strain system matching filter can be selected for a "best fit." Finally, solid state amplifiers can be substituted for the phototube amplifiers in the present inertial system. This last method would produce better overall results. Solid state amplifiers for use in the Alaska Long-Period Array (ALPA) inertial seismographs are being tested in the laboratory on another program and results are generally good. Their use in the strain system inertial seismograph design would upgrade the inertial seismographs and provide fewer problems in matching the responses of the strain and inertial systems.

2.2 ULTRA LONG-PERIOD (ULP) OUTPUT

In order to take full advantage of the capability of strain instruments to detect ultra-long-period seismic waves, an ULP output from each seismograph component will be provided. The amplitude response of this output will be similar to the ALPS response discussed above but will be one decade lower in frequency. Extended efforts to achieve a particular seismograph sensitivity at these longer periods are not planned. However, data recorded on the ULP channels will provide additional information useful in improving long-period wave discrimination capability.

3. DETERMINE THE MOST EFFECTIVE TECHNIQUE, TASK a(2)

The two most promising techniques for strain seismometer design are the moving coil-permanent magnet technique and the direct current-variable capacitance (DC-VC) technique. These techniques will be thoroughly explored before further consideration is given to the laser-interferometer or the radio frequency-variable capacitance (RF-VC) techniques.

3.1 MOVING COIL TECHNIQUE

The horizontal strain seismometers at the Wichita Mountains Seismological Observatory (WMSO) use moving coil-permanent magnet transducers. These transducers have been found to be very stable and reliable since their installation about 5 years ago. The magnets used are the largest that were then available and are charged to a high flux density of 1.0 tesla (10,000 gauss). Larger magnets are now available which can be used in a modified version of the present magnet design. Their use will result in a 20 to 30 percent increase in flux density in an air gap of the same dimensions as the present design.

The transducers at WMSO require a relatively low impedance coil (800 ohm) to provide the greatest efficiency in energy transfer between the coil and the 1100 ohm galvanometer. However, the LP strain seismographs for this project will use solid state amplifiers which require high impedance coils for greatest efficiency. Use of high impedance coils will provide generator constants about 10 times higher than the present design. The resulting increase in Johnson noise due to higher coil impedance is not as great as the increase in generator constant. Therefore, the high impedance coil-solid state amplifier combination will provide higher overall sensitivity than the present low impedance coil-phototube amplifier combination.

The velocity sensitive moving coil technique offers an advantage over displacement techniques by eliminating the problems created by very long-period, high amplitude earth tides and secular strains. By incorporating the above improvements and increasing the pier separation from 20 to 40 meters, the desired seismograph resolution can be achieved.

3.2 DIRECT CURRENT-VARIABLE CAPACITANCE TECHNIQUE

The principle of the direct current-variable capacitance transducer has been used for many years in audio microphones. It functions by virtue of the fact that if the charge on a capacitor is held constant as the capacitance is varied, the capacitor voltage will also vary. The principle of operation may be shown mathematically as follows. The expression for capacitor charge is given by

$$Q = CV \tag{1}$$

where Q is the stored charge, C is the capacitance, and V is the voltage.

Differentiating equation 1, assuming small changes, setting the differential quantitites approximately equal to the change in the quantity, and setting the change in charge ΔQ equal to zero yields

$$\frac{\Delta V}{V} = -\frac{\Delta C}{C} \tag{2}$$

A study of available materials and techniques indicates that a DC-VC transducer for the long-period strain work is both feasible and practical.

3.2.1 Circuit

The circuit being considered for this application is a modification of a basic charge amplifier in that the variable capacitor is placed in the feedback loop rather than in the input circuit. By using this technique, the low frequency cutoff can be readily controlled by simply adjusting the equivalent leakage path resistance. Figure 3 is a schematic of such a circuit which has been used for feasibility tests. Another feature of this circuit is that the high 1000 MΩ equivalent resistance is obtained with lower resistances in a T-pad in the feedback loop.

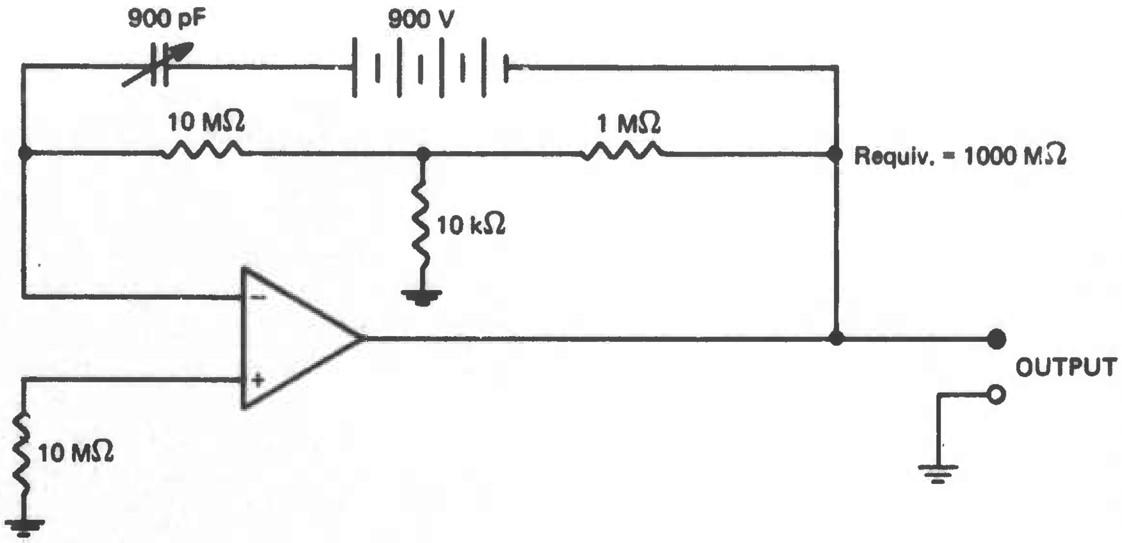

Figure 3. Schematic of a variable capacitance transducer used for feasibility tests

3.2.2 Sensitivity

Inspection of equation 2 reveals that for a given variable capacitance transducer, the signal output (ΔV) increases proportionally to the applied voltage. To illustrate the possibilities of this concept, an example is useful. If the noise of the system is such that 1 μV is the smallest detectable signal (ΔV) and the transducer voltage (V) is 1000 V, then capacitance changes on the order of one part per billion are detectable.

3.2.3 Frequency Response

The DC-VC transducer is inherently a high pass transducer with a response slope of -6 dB/octave below the high-pass cutoff. It tends to reject those signals which are of much longer period than the signal of interest, i.e., the earth tide and the secular strain. In the case of the earth tide, however, the rejection is incomplete and the earth tide signal will be larger than the desired signals. This is discussed in a later section. The high pass characteristic does relieve the dynamic range requirements of the electronics.

The low frequency response of the DC-VC transducer is a function of the transducer capacitance and its leakage path impedance. Variable capacitors are inherently of low capacitance as a result of air dielectrics and therefore high impedance must be synthesized using operational amplifier techniques.

4. DESIGN, FABRICATE, AND TEST LABORATORY MODELS, TASK b(1)

The preliminary results of the investigation task indicate that either of the two electromagnetic transducer techniques discussed above will provide a strain seismograph with the necessary sensitivity. The approach selected for this task is to design and fabricate laboratory models of both the moving coil-permanent magnet and the dc variable capacitance transducers, test them in a stable environment, and make a final decision on the technique to be used on the results of those tests. Since both of these transducers will require strain rods, design of the rod and rod support assemblies has been started.

4.1 MOVING COIL TECHNIQUE

4.1.1 Coil and Magnet Assembly

Figure 4 is a sketch of the laboratory model coil and magnet assembly designed for the project. The cylindrical magnet is composed of eight wedge-shaped segments of Alnico 5 material weighing a total of about 110 kilograms (250 lb). The segmented construction is necessary due to casting and heat treating size limitations imposed by the manufacturing process. The magnet is mounted inside the soft steel pole pieces to limit stray flux leakage. The steel components have sufficient cross-sectional area to prevent saturation at the high magnet charge expected.

The coil assembly presently in use on the horizontal strain instruments at WMSO consists of a coil cemented to a thin epoxy coil form and supported by a cast aluminum alloy hub. The design of the coil form and its support for this application makes use of techniques which will provide an assembly with much lower mechanical noise. The coil form and its support are of one piece construction. This construction eliminatates joints between materials with different expansion coefficients which creak with temperature changes. The material used is a glass-fiber, reinforced-epoxy laminate which has about half the expansion coefficient of the aluminum of the present design. The coil itself is random wound in epoxy and is 1.2 in. long. By making the coil longer than the 1 in. magnet pole length as shown in figure 4, the stray flux outside the gap can be utilized to further increase the transducer generator constant while maintaining linearity.

The calculated specifications of the transducer are as follows:

Magnet Assembly

Magnet material	Alnico 5
Flux density in gap	1.3 T (13,000 G) stabilized
Dimensions	506 mm (20 in.) diameter x 305 mm (12 in.) long
Weight	330 kg (730 lb) approx

Coil Assembly

Wire size	#39 AWG
Number of turns	19,000
Total wire length	18,500 m
Resistance	51,500 Ω

Generator Constant — 20,100 V/m/sec, minimum.

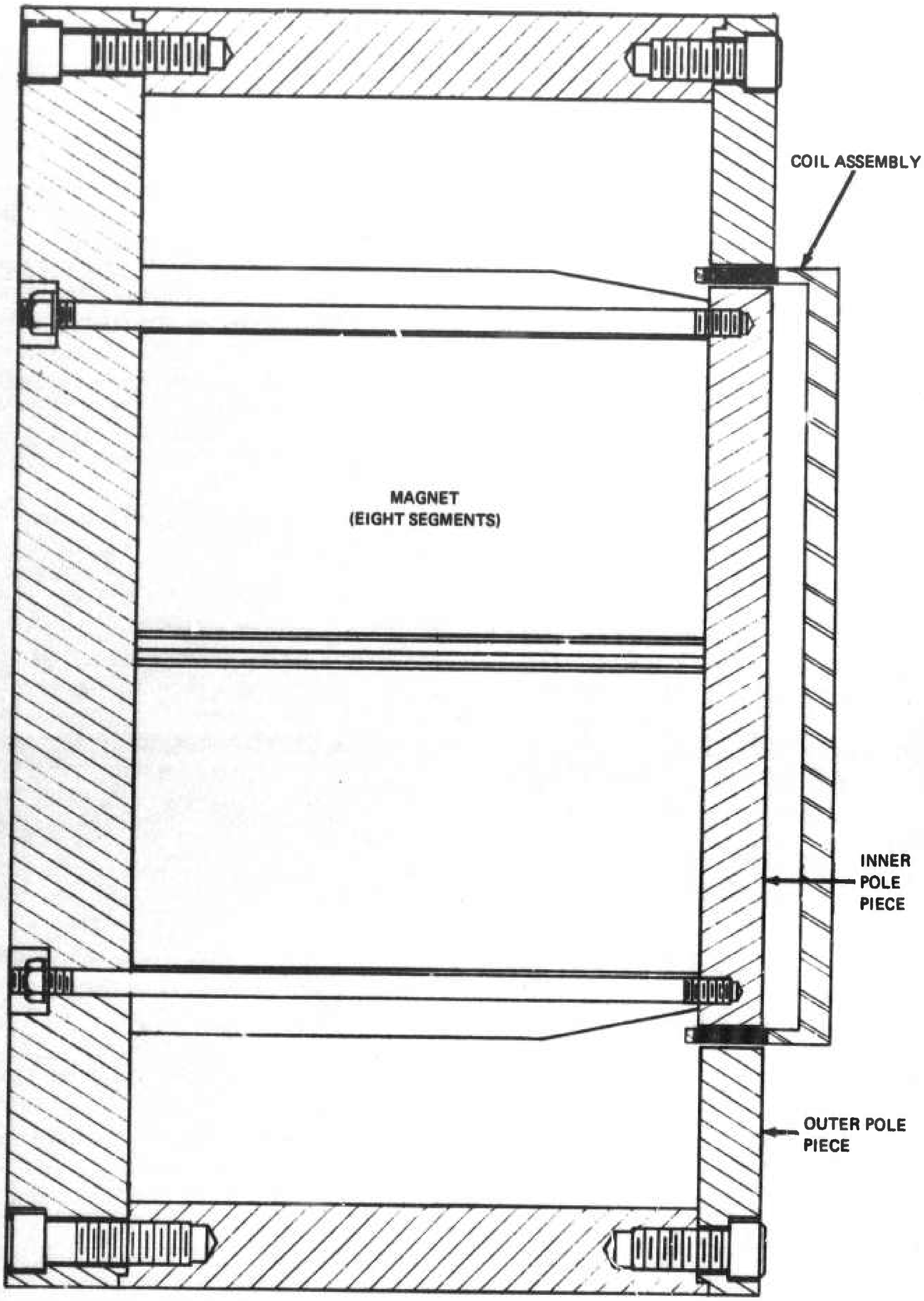

Figure 4. Sketch of the laboratory model moving coil-permanent magnet transducer for strain seismometers

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4.1.2 Solid State Amplifier

The amplifier selected for use with the moving coil transducer is the Ithaco, Inc., Long-Period Seismic Amplifier, Model 6089-34. The specifications state a gain of 80 dB with maximum noise referred to the input of 2.5×10^{-8} V rms in the pass band from 0.003 to 0.033 Hz. This amplifier is similar to the amplifier being supplied by Ithaco for the Norway LP Array.

The decision to buy the Ithaco amplifier was based on the requirements of the project. Noise tests performed previously by Geotech and further noise tests performed on a Philbrick operational amplifier, Model SP2A/X, and an Ithaco, Model 154, contributed to the decision. The Texas Instruments, Inc., Model RA-12 LP amplifier was not available for simultaneous testing. The test results indicated that the Ithaco amplifier was slightly quieter than the Philbrick unit. It was also found to be much less susceptible to environmental changes. Since the Philbrick and the Texas Instruments units would have required design of feedback circuits, power regulation circuits, and environmental packaging, the Ithaco amplifier was selected.

The amplifier was ordered on 29 August and received on 23 September. Detailed amplifier tests, including noise level and response tests, will begin in the laboratory during October.

4.2 DIRECT CURRENT VARIABLE CAPACITANCE TECHNIQUE

4.2.1 Transducer Design

4.2.1.1 Variable Capacitance

Neglecting fringe effects, the capacitance between two parallel plates is given by

$$C = K \varepsilon_o \frac{A}{d} \qquad (3)$$

where K is the dielectric constant of the material between the plates (K = 1 for free space), ε_o is the permittivity of free space, A is the plate area, and d is the distance of separation. To vary the capacitance, one may vary the plate area, the plate separation, or the material between the plates. Variable plate separation is easier to achieve and will provide the greatest sensitivity for a given transducer size. For motions very much smaller than the separation distance, the variable plate separation technique is quite linear.

Differentiation of equation 3 with respect to d then dividing by equation 3 yields

$$\frac{\Delta C}{C} = - \frac{\Delta d}{d} \qquad (4)$$

and from equations 2 and 4

$$\frac{\Delta V}{V} = \frac{\Delta d}{d} \qquad (5)$$

Equation 5 not only shows the transducer to be linear for motions very much smaller than d, but also that the sensitivity is independent of the total capacitance. Sufficient capacitance is required only to achieve the required frequency response.

With plate spacing set at the nominal minimum value of 2.5×10^{-4} m, secular strain of approximately 1×10^{-4} m p-p could result in a change in sensitivity of plus and minus 20 percent. This can be minimized by using a differential capacitance transducer in which one set of plates is opening while the other is closing as shown in figure 5. The signals (ΔV) from the two halves are made to have the same polarity by reversing the battery polarities.

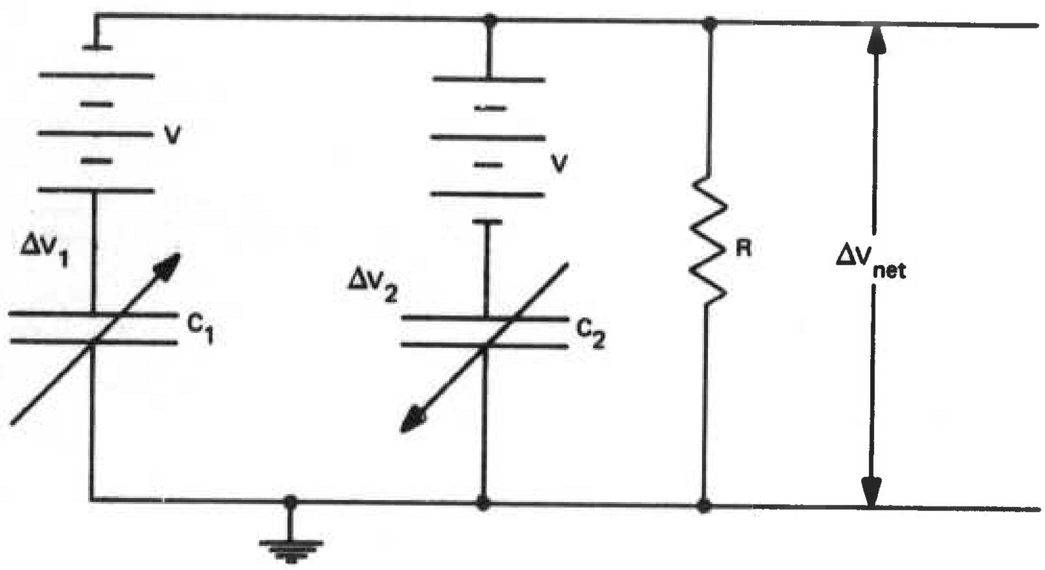

Figure 5. Differential variable capacitance transducer for achieving constant sensitivity in the presence of secular strain

The differential connection achieves nearly constant sensitivity not only through partial cancellation of the 1/d characteristic of the capacitors, but also as a result of charge transfer between the two transducer parts. Analysis of this effect, assuming equal areas for the two sets of plates, gives a sensitivity of

$$\frac{\Delta V}{V} = \Delta d \left[\frac{d_1^2 + d_2^2}{d_1 d_2 (d_1 + d_2)} \right] . \qquad (6)$$

The bracketed term is seen to be relatively independent of the value of either d. The sensitivity is a minimum for $d_1 = d_2$ and increases only slowly with transducer motion either side of center.

Linearity increases with increasing nominal value of d for either single ended or differential operation, but for the same linearity greater sensitivity is achieved differentially. If a maximum sensitivity change of 5 percent is desired over the peak-to-peak secular strain for a 20 m strain rod (approximately 1×10^{-4} m p-p), then the separation at mid-range must be

$$d_{mid} = 3.25 \times 10^{-4} \text{ m (0.0128 inch)}$$

for a differential connection (equation 6), or

$$d_{mid} = 20.8 \times 10^{-4} \text{ m (0.082 inch)}$$

for a single ended connection (equation 5).

The differential operation yields more than six times the sensitivity of the single ended mode with the same linearity.

4.2.1.2 Signal Level

The signal level may be calculated using equation 5 or 6. For a 20 m strain rod, the minimum strain of interest is approximately 1×10^{-11} m p-p at 30-second period. By using a voltage of 1000 V and capacitor spacing of 0.33 mm, the minimum signal level at the amplifier output is 30 μV, which is a practical level.

4.2.1.3 Capacitor Area

The RC time constant required for response to 100-second period is 16 seconds. If 1000 MΩ is assumed to be the largest practical value of R, then C = 0.016 μF. Using equation 3 and d = 0.33 mm, the required area for an air capacitor is 0.60 square meter total or 0.3 square meter per section for the differential transducer. By use of interdigitated plates, the volume required for the transducer will probably be no more than that of a 1 gallon container.

4.2.2 Feasibility Tests

The circuit of figure 3 was breadboarded and tested. The variable capacitor was from a high voltage radio frequency transmitter and was of the variable area type. Using equation 2, the expected sensitivity is calculated as 1 volt per picofarad for the values shown in figure 3.

Theory and experimental data showed good correlation. Better correlation would have been obtained if the circuit time constant had been longer. The time constant of 0.9 second did not give a sufficiently accurate reading of the voltages produced as a result of the capacitance changes.

4.2.3 Problems Encountered

A number of problems have been encountered which have delayed progress.

4.2.3.1 Noise

The 0.1 pA p-p noise current flowing into the amplifier input terminal yields 100 μV p-p noise at the amplifier output due to the effective 1000 MΩ source impedance. This noise has prevented realization of the full motion sensitivity of which the method is inherently capable.

4.2.3.2 Oscillations

In practice, the breadboard circuit has had much more noise than indicated above. This is apparently due to self oscillations within the amplifier. Standard stabilization procedures have so far failed and the amplifier manufacturer has been unable to offer any explanation.

4.2.3.3 Amplifier Failures

All operational amplifier modules tested so far have failed after several hours of operation, even with protective circuitry not shown in figure 3. The reason for this has likewise escaped even the amplifier manufacturer.

4.2.3.4 Dielectric Liquid

The large leakage impedance required to obtain the desired frequency response produces the noise discussed above as well as other problems. This impedance could be reduced if a suitable dielectric liquid filled the volume between the capacitor plates. Such a liquid not only must have a high dielectric constant, but must have a high volume resistivity. The transducer shunt resistance must be at least ten times that of the effective leakage path which determines the frequency response. For the plate area and spacing calculated above, a volume resistivity of 10^{16} ohm-cm is required. Such large resistivity has only been found in materials with dielectric constants less than 2 to 3.

Dielectric constant and resistance measurements were made on several liquids, none of which are completely satisfactory. The results are shown in table 1. The tests were made using a 200 pF radio frequency, high voltage, variable capacitor. The resistances shown would be about fifty times lower if the test liquids were installed in the actual transducer because it will have greater plate area and smaller plate spacing than the test capacitor.

Table 1. Measured properties of various dielectric liquids

Dielectric	Dielectric constant	Resistance MΩ	Notes
Air	1.0	900,000	Capacitor leakage
Isopropyl alcohol	--	0.038	
Silicone fluid DC200	2.77	1,200	

Table 1. (Continued)

Dielectric	Dielectric constant	Resistance MΩ	Notes
Auto transmission fluid	2.16	5,000	
Mineral oil (USP)	2.05	900,000	Oil conductivity immeasurable
Peanut oil	3.0	1,000	
Ethylene Glycol	83?	<1	Conductivity so high that capacitance readings were inaccurate
Glycerine (96 percent)	500?	<1	
Caster oil	4.38	2,000	

The data in table 1 indicate that only the mineral oil has the required impedance. The dielectric constant is low, but it is, at the very least, better than air. Transformer oil has a slightly higher dielectric constant, and probably has adequate impedance, but has not yet been tested.

Solids in general have a much higher impedance than liquids for the same dielectric constant. With this in mind, reagent grade titanium dioxide ($K \approx 100$) powder was mixed with the mineral oil in an effort to produce a suspension with high impedance and high dielectric constant. The effective dielectric constant was higher but the impedance was reduced to an unacceptable value of 600 megohms. Apparently the surface resistivity of the powder grains is nearly three orders of magnitude lower than the volume resistivity.

The result is that a reduction of 2 to 3 in the required leakage impedance for a given capacitor volume is all that can be achieved by using a dielectric liquid.

4.2.4 Other Design Factors

4.2.4.1 Earth Tide

The circuit of figure 3 has a simple RC roll off (6 dB/octave) at low frequencies. If it is 3 dB down at 100-second period, it will be 50 dB down at the 45,000-second period of the earth tide. The earth tide, however, is 80 dB above the signals to be measured at 30-second period, resulting in a detected earth tide signal which is 30 dB above the 30-second period signal. Clearly, a faster roll off rate is desirable.

4.2.4.2 Interplate Forces

The high voltage between plates produces significant forces to be considered in the transducer design. Neglecting fringe effects, the attracting force between two parallel capacitor plates is given by

$$F = \frac{K\varepsilon_0 A V^2}{2d^2} \tag{7}$$

Using the values discussed previously, the force is 24.0 N for a plate spacing of 0.33 mm. These forces balance for the differential configuration of figure 5 at the midrange point. The large secular strains, however, produce a net force unbalance of 7.6 N at the extremes. This force may place the strain rod in tension or compression depending upon which side of the midpoint the transducer lies. A tensile bias in excess of this amount must be applied to avoid column loading of the strain rod.

4.3 STRAIN ROD AND ROD SUSPENSION DESIGN

Since the two more promising techniques will require mechanical connection between the piers, design work has been started on the strain rod and rod suspension with primary emphasis on the horizontal seismometers. Since the vertical seismometer will be installed either in a borehole or in a vertical mine shaft, its design cannot be completed until a specific mine is selected.

The present horizontal strain seismometer uses fused quartz tubing suspended by wire slings inside a pressure-tight steel housing. Since the strain instruments for this project will be installed in a sealed mine, the pressure-tight housing can be eliminated and the rod supports can be improved. Simple covers over the rod can be designed to minimize air convection currents. This will result in a less complicated design which will be stable and easier to install and maintain.

Four materials have been considered for the rod: fused quartz, Invar, steel, and CER-VIT. An extremely low expansion ($1.5 \times 10^{-7}/°C$) ceramic material, manufactured by Owen-Illinois, Inc., under the trademark CER-VIT, was eliminated due to high cost. Invar tubing is available and offers several advantages over the fused quartz now being used. It is not subject to breakage and would not require as much care during installation and maintenance. It can be easily joined by external couplers which would allow line of sight inspection through the tube, greatly simplifying the alignment procedure. Finally, fixtures can be clamped to the tube, allowing support configurations different from the present sling arrangement. Design calculations show that a tube with an outside diameter (o. d.) of 51 mm (2 in.) and a wall thickness of 1.6 mm (1/16 in.) would be acceptable. Steel offers the same strength advantage as the Invar, but the disadvantage of the higher coefficient of expansion is not offset by a material cost reduction.

A number of seismometer design factors based on the requirement for a 40 m long strain interval for moving coil transducers and based on the use of Invar tubing of 2 in. o. d. and 1/16 in. wall thickness have been examined. Of immediate concern is the control of tube motion that can cause loss of strain signal as well as undesirable amplitude and phase effects in the frequency band of interest. These factors are discussed below.

4.3.1 Longitudinal Motion

4.3.1.1 Natural Frequency

The computed natural frequency of vibration, f_n, of the 40 m Invar tubing along its longitudinal axis is 35 Hz. The addition of transducer mass at the free end of the tube has a small effect on the natural frequency. For example, in the case of the moving-coil transducer, the mass of the coil and coil mount, estimated at 2.7 kg, will lower f_n by 5.5 percent.

4.3.1.2 Degree of Damping

A limit on the degree of damping is required to restrict undesirable phase shifts to 5 degrees or less below 0.1 Hz. By treating the strain seismometer as a spring-mass system and dividing its equation of motion by f^2, the maximum value of h (ratio of actual damping to critical damping) that can be tolerated is given by

$$h = \left[\frac{1 - (f/f_n)^2}{2f/f_n} \right] \tan \Theta. \qquad (8)$$

If f_n = 33 Hz, f = 0.1 Hz, and Θ = 5 degrees, then h = 14.4.

It is seen that the damping factor in the case of a strain seismometer operating in the long-period range is not an important parameter unless the motion along the longitudinal axis is greatly overdamped.

4.3.1.3 Electrical Stiffness

Another factor that could cause loss of signal due to compression of the tube is the electrical stiffness of the system. This factor is of significance only when using the moving-coil transducer and galvanometer. In the case of the moving coil and solid state amplifier combination, the electrical stiffness is negligible. The loss is also negligible when using a balanced variable capacitance transducer.

4.3.1.4 Ratio of Strain to Inertial Effect

The strain seismometer is a spring-mass system. To determine whether the longitudinal stiffness of the tube is sufficient to prevent inertial motion (u_i) of the end of the tube from over-riding differential motion (Δu) of the anchor points at f = 0.1 Hz, let the horizontal differential motion be expressed by

$$\Delta u = 2\pi f \, u_g \, L/c \qquad (9)$$

where

u_g = earth particle motion

L = strain interval between anchor points

c = velocity of Rayleigh waves at f = 0.1 Hz

Letting the response of the inertial system be given by

$$\frac{u_i}{u_g} = \frac{1}{\sqrt{\left[1 - \left(\frac{f_n}{f}\right)^2\right]^2 + \left(2h\,\frac{f_n}{f}\right)^2}} \qquad (10)$$

and combining equations 9 and 10 yields

$$\frac{\Delta u}{u_i} = 2\pi f \frac{L}{c} \sqrt{\left[1 - \left(\frac{f_n}{f}\right)^2\right]^2 + \left(2h\,\frac{f_n}{f}\right)^2} \qquad (11)$$

Substituting h = 1.0, f = 0.1 Hz, L = 40 m, c = 3.0 km/sec,

$\Delta u/u_i$ = 835, which shows that long period strain signals, in effect, will be free of inertial motion.

In the case of the vertical strain seismometer, where vertical strain is 1/3 of the horizontal strain when equal horizontal and vertical particle motion exists, $\Delta u/u_i$ = 278 at f = 0.1 Hz. In this case, long-period strain signals will contain less than 1 percent contamination by inertial motion.

4.3.2 Transverse Motion of the Tube

4.3.2.1 Natural Frequency of Vibration

In the case of a vertical strain seismometer without lateral constraint along the tube, and in the case of a horizontal strain seismometer with sling suspensions, horizontal transverse motion can occur with the nodal points of the fundamental mode occurring at the ends of the tube. Using the case for the fixed and hinged beam, the natural frequency of the fundamental mode is given by Church (1957)

$$f_n = 2.45 \sqrt{\frac{gEI}{wL^4}} \qquad (12)$$

where

- g = acceleration due to gravity = 9.807 m/sec^2
- E = modulus of elasticity for steel = 2.07 x 10^{11} N/m^2
- I = moment of inertia = 7.5 x 10^{-8} m^4
- w = weight per unit length of tubing = 18.7 N/m
- L = length of tube = 40 m

For the 40 m Invar rod, f_n = 0.14 Hz.

To eliminate vibration at 0.14 Hz (7.2 seconds) supports will be placed along the strain rod to shorten L. Using the case of a simply supported beam as a close approximation, since this case gives the lowest value of frequency which will interfere with the measurement of long-period signals, the frequency of vibration with 1.5 m suspended sections is given by Church as

$$f_n = \frac{n^2 \pi}{2} \sqrt{\frac{gEI}{wL^4}} \qquad (13)$$

$$= 61 \text{ Hz},$$

where n = vibration mode number = 1.

4.3.2.2 Suspension Design

Strain rod suspension design efforts have been confined to the horizontal seismometers because the method of installing the vertical seismometer cannot be determined until a specific mine is selected. If the vertical instrument is installed in a mine shaft, techniques developed for the horizontal rod suspension can be adapted to the vertical case. If, however, the vertical instrument is installed in a borehole, methods of remotely aligning and supporting the rod must be developed. A rod suspension assembly for the horizontal seismometers has been designed and two units are being fabricated for laboratory testing. The assembly consists of a triangular frame of steel channel. Wires or spokes extend at 120 degree angles from a clamp ring on the tube to clamps mounted in each corner of the triangle. The primary advantage of this arrangement is that it greatly limits transverse vibration while allowing reasonable freedom of longitudinal motion of the rod.

5. DEVELOP A FINAL ENGINEERING MODEL DESIGN, TASK b(2)

This task is based upon results of task b(1). No work has been performed on this task during this reporting period.

6. DESIGN A FIELD TEST INSTALLATION, TASK b(3)

This task includes, among others, a subtask to select a mine suitable for installation of the three-component strain seismograph. A map study was made to list mines to be inspected by a geologist to determine their applicability. Two areas were chosen for primary investigation: the area within a two hundred mile radius of the Tonto Forest Seismological Observatory (TFSO) and the area near the present Long-Range Seismic Measurements (LRSM) program site at Las Cruces, New Mexico. In mid-August, a geologist was sent to the field to visit several mines in these areas and to make a tentative selection of a few mines which met all or most of the requirements. Preliminary investigation was completed in late September. Final selection will be made during late October and early November.

6.1 MINE SELECTION CRITERIA

Criteria for selection of a mine suitable for installation of the long-period strain seismograph system were established as follows:

a. Commercial power will be available to the site.

b. The site must be accessible to heavy equipment during the initial phase of the installation and accessible to light vehicles after the system is operational.

c. Mine requirements are as follows:

(1) One vertical shaft and two horizontal tunnels, all of which are perpendicular to each other.

(2) The shaft and two tunnels must be within a reasonable distance of each other.

(3) The shaft and two tunnels must be at least 45 m (150 ft) in length.

(4) The shaft and tunnels must be dry or nearly so.

(5) The shaft and tunnels must be safe to enter or in such a condition that a safe condition could be attained at a reasonable cost.

(6) The shaft and tunnel must be capable of being sealed to reduce wind currents and to stabilize the temperature.

d. Geological requirements are as follows:

(1) Bedrock should be as competent and homogeneous as possible.

(2) Igneous bedrock is preferable to sedimentary or metamorphic bedrock.

(3) All three instruments should be emplaced in the same lithologic type of bedrock if at all possible.

(4) Geology of the area should be as simple as possible.

(5) Faults between the two ends of any of the instruments will be avoided.

e. The noise requirements for a typical LRSM seismic station apply to a strain seismometer installation. Some of the minimum distances from a noise source to produce a negligible effect are given below.

(1) Frequently used logging or mining roads - 1 mile;

(2) Farm roads or infrequently used logging and mining roads - 1/4 mile;

(3) Oil-well activities, drilling, or pumping - 2 miles;

(4) Railroads - 2 miles;

(5) Large rivers, lakes, bays, and oceans should be avoided;

(6) Active volcanic and active tectonic regions should be avoided;

(7) Hydro-electric generators should be avoided;

(8) Large mining operations - 10 miles;

(9) Small mining operations - 5 miles.

These distances are not fixed because their effect upon an installation will vary greatly from one area to another. The effect a given noise source will have on the installation will be left to the judgement of the site selector.

6.2 MINES NEAR THE TONTO FOREST SEISMOLOGICAL OBSERVATORY

Several mines in the immediate vicinity of TFSO were visited and all but one were eliminated due to mining activity, standing water, or inaccessability. The Old Waif Mine, the only exception, is near instrument Z16 of the TFSO short-period array. It consists of a straight horizontal passage about 60 m long in the north by northwest direction and a perpendicular horizontal tunnel of about 100 m that will require about 10 m of straightening in the middle. The rock is a competent altered granite. To make the mine suitable for instrument installation, it will be necessary to shore the entrance and drill or dig a shaft for the vertical instrument. It will also be necessary to construct a power line approximately 3 miles long and improve 1.3 miles of access road.

Mining areas within a 200 mile radius of TFSO were also investigated. In each area visited, persons familiar with the area were contacted and those mines thought to be suitable were visited. No mines were located in this area which met the primary requirements. These mines were eliminated on the basis of one or more of the following conditions: unavailability of power; noise generation due to geology, lakes, and local mining activity; and water in the mines.

Time did not permit investigation of many mines in this area. Subsequent discussions with a mining engineer and other persons in the Payson area have indicated that a few mines in the Rich Hills area south of Prescott and some in the Little Harquehala Mountains near Salome, Arizona, may be suitable. These areas will be visited later.

6.3 MINES NEAR LAS CRUCES, NEW MEXICO

The Stevenson-Bennett mine at the LRSM Las Cruces site was thoroughly explored and found to meet many of the requirements for instrument installation. The rock in the major portion of the mine is dolomite. Horizontal instruments could be installed on the main level where the LRSM instruments are now being operated. It may be possible to install the vertical instrument in one of the shafts or stopes. However, sealing of the instrument areas may be difficult since the mine consists of several levels of interconnecting shafts, stopes, and tunnels. Also, some cleaning and shoring would be necessary. Power and telephone lines are complete to the site and the access road is in reasonably good condition.

The Doña Dora mine, located about 5 miles northeast of the Stevenson-Bennett mine on the White Sands Missile Range (WSMR) is very promising. Although a cave-in about 150 m from the mine entrance prevented complete examination, the preliminary survey indicates that the mine is in good condition. The rock is granite. Dunham (1935) indicates that the mine consists of a tunnel extending about 175 m from the entrance in a westerly direction, then north approximately 50 m, then west again for about 300 m. Dunham also indicates two vertical shafts in which it may be possible to install the vertical instrument. To make the mine safe and usable, a vertical shaft at the mine entrance would require covering and debris should be removed from the mine. Power is available from the WSMR facilities about 2 miles distant. About 1/2 mile of access road improvements will be necessary.

The remaining mines visited in this area were either considered unsafe or accessable only by vertical shafts and were eliminated.

7. ENGINEERING CHANGE PROPOSAL

An Engineering Change Proposal (ECP) designated P-1347, was submitted to the Project Office and to Headquarters, Aeronautical Systems Division, on 25 September. It is a proposal to include in the contract the manufacture, installation, and preliminary operation of all the equipment necessary to obtain LP strain seismic data for LP wave discrimination as soon as possible. Refer to P-1347 for details of the proposed tasks.

8. REFERENCES

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13. ABSTRACT

The design of strain seismographs capable of detecting long-period seismic motion is in progress. The moving coil-permanent magnet and the direct current-variable capacitance techniques appear to be the most promising and laboratory models of transducers using these techniques are being constructed for testing. Many mines in the Payson, Arizona, and the Las Cruces, New Mexico, area have been visited. Three mines meeting many of the requirements for instrument installation were located and could be used if necessary improvements are made. ( )

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