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VESIAC State-of-the-Art Report

THE REQUIREMENTS OF A HIGH-SENSITIVITY SEISMOGRAPH STATION

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PREFACE

VESIAC, the VELA Seismic Information Analysis Center, is an information collection, analysis, and dissemination facility established at the Institute of Science a and Technology of The University of Michigan. The contract is sponsored by the Advanced Research Projects Agency under the Office of the Secretary of Defense.

The purpose of VESIAC is to analyze the research information related to the VELA UNIFORM Program of Project VELA and to function as a central facility for this information. The facility will serve all authorized recipients of VELA UNIFORM research information by issuing subject bibliographies with abstracts and special reports as required. In addition, VESIAC will periodically summarize the progress of the research being conducted.

VESIAC is under the technical direction of the Acoustics and Seismics Laboratory of the Institute. In its operation VESIAC draws upon members of this laboratory and other members of the Institute and University.

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ABSTRACT

The efficiency of a short-period seismograph is regulated largely by the nature and magnitude of the so-called background noise prevalent at the station. This background noise is more or less continuous and varies from place to place and from time to time. Effects of this noise may be reduced by (1) selecting a station site where the noise is low, either remote from noise sources, in the shadow of noise barriers, or deep underground; or by (2) the use of frequency and wavelength filters. Frequency filters are in large part ineffective because the signals we wish to measure have the same frequency (from 0.5 to 5 cps) as the noise; and wavelength filters require the use of expensive arrays.

This report discusses possible sources and methods of propagation of background noise and the selection of optimum sites and methods for reducing the effect of noise. Present and suggested future arrays are included in this discussion. Highly sensitive seismograph stations and instruments in current operation are described, and comparisons are made of the ability of some of the better stations to record magnitude 4 to 5.5 earthquakes. Suggested designs of unmanned and other special-purpose seismic stations are included.

THE REQUIREMENTS OF A HIGH-SENSITIVITY SEISMOGRAPH STATION

1

INTRODUCTION

A short-period seismograph is defined as one which shows peak sensitivity to vibrations of the earth having periods from 0.2 to 2 seconds with a fall-off toward zero for infinitely long and infinitely short periods. These instruments have great importance in modern seismology because the periods of initial P waves from nearly all earthquakes and large explosions are in this range. Unfortunately, the periods of the ever-present disturbances in the ground are also in this range. The problem therefore is not how to obtain greater magnification from the instruments, as that is now almost unlimited, but how to obtain the greatest effective magnification in relation to these ground disturbances, called background noise.

In 1956 I discussed the optimum setting for a high-sensitivity short-period seismograph, using largely the basis of my own experience [1]. Since then much has been done toward seismic background surveys: many new stations have been placed in operation, and the experience thus gained has become available; new instrumentation has been designed; and methods of recording and data processing have been improved. This report discusses an optimum short-period seismograph station from the viewpoint of 1963.

During the first six decades of this century, seismometry has advanced from crude mechanical devices to the highly modern moon seismometers which are capable of broadcasting their motion across space to earth-bound recorders.

The early inverted-pendulum models, although crude, are not obsolete. Many are still in operation, some at highly rated observatories and others in localities where photographic paper is scarce. Since the record is made by a stylus on a rotating cylinder of smoked paper, magnification is attained through the use of a heavy mass, necessary to overcome friction, and a delicately constructed system of levers. Twenty-ton masses are not uncommon. Inverted pendulums have 2 degrees of freedom and record in two horizontal directions. In Switzerland, the masses are suspended on a heavy spring and recording is in the three cardinal directions. Magnification attained by mechanical seismographs varies from 10 to about 2000, the latter attained with use of a 20-ton mass. These systems record ground motion with periods up to 2 or 3 seconds. Damping is attained by means of a plunger in a confined air space or in a dashpot of low viscosity oil. The mass of a 20-ton seismograph fills the larger part of an ordinary-sized room. The one at Zurich, for example, consists of a metal tank filled with discarded World War I armament.

In contrast with the 20-ton seismograph is the Wood-Anderson seismograph [2], developed in the earlier 1920's, with its 0.7-gram dynamic mass. Ground periods up to about 0.8 seconds can be magnified about 2600 times; this is possible because the displacement is registered on a rotating cylinder of photographic paper by use of optical levers, which have no friction. The mass consists of a 1-mm diameter copper rod and mirror suspended longitudinally in a near vertical position on a ribbon rolled from a 20-μ diameter tungsten wire. The device acts as an accelerometer for ground frequencies less than 1 cps (periods greater than 1 second). It goes into bowstring resonance at about 20 cps and fails as a seismometer for these and greater frequencies [3, 4]. The intermediate-period Wood-Anderson seismograph has a thin bar for a mass and directly records ground periods up to 6 or 7 seconds except that it likewise fails at bowstring resonance. Its magnification is about 500. Electromagnetic flux in the copper vane provides the damping in both cases.

Trends toward modern seismometry were under way by 1914, when Prince B. Galitzin developed and described the electromagnetic seismograph that bears his name [5]. A number of modifications of Galitzin's method have been made. One is the Benioff variable-reluctance (VR) seismograph (1932). In the two decades following, various moving-coil (MC) types, including the Benioff, Sprengnether, Wilson-Lamison, Lehner-Griffith, and others, were produced. The modifications mentioned are earth-driven instruments without amplification other than the direct electrical connection between the seismometer and galvanometer, with an intermediate shunt and resistance pad to provide gain control and internal damping. In most areas, the gain is high enough that the background noise limits additional gain. This background noise, its causes, and possible methods of its reduction are subjects of later sections of this report.

The Benioff VR and MC and similar instruments have another characteristic in common. They have peak sensitivity to periods near 1 second and are relatively insensitive to the long-period surface waves that are propagated from most large earthquakes. The fact that P waves from most distant earthquakes also have periods near 1 second was largely responsible for the immediate success of the Benioff instruments.

The Benioff VR long-period seismometers developed by Press, Ewing, and others, and a strain seismometer developed by Benioff, drive long-period galvanometers and are sensitive to long earth periods. Discussion of these instruments is outside the scope of this article.

As for applied geophysics, the seismic method of exploration geophysics was developed during the 1920's, and by 1930 salt domes in the Gulf of Mexico area had been discovered by that method. During the succeeding decades, instrumentation and practices reached a high state of perfection. However, until recently applications of this art to earthquake seismology were not successful, chiefly because exploration geophysicists were interested primarily in arrival times and their gear was tuned to record high-frequency vibrations—not generally prevalent in seismic waves from earthquakes.

In the past few years, largely because of the demands brought about by a national emergency, exploration and earthquake seismologists are finding a common meeting ground and are calling on other services, such as the communications services, for assistance. The result is present-day seismology with its greater and greater world coverage with better and better instruments, and with greater and greater emphasis on getting the most from the data on the resulting records.

2

BACKGROUND NOISE

In seismology, the term "background noise" applies to all ground unrest identified on the record as continuous or intermittent disturbances not originating from earthquakes. These disturbances, which may vary from hour to hour and from place to place, may result from to and fro bodily translation of the earth particle, as in a bowl of jelly, or from vibrations set up by passing elastic waves. The former are more applicable to spongy ground or saturated fill, and the latter to firm ground and rock. Background noise resulting from traffic, machinery, or wind on buildings, trees, or rocks is usually high in frequency, with periods somewhat less than a second. Such disturbances, troublesome only to short-period instruments or to instruments that have vibrating parts that may be set into resonance by the disturbances, are referred to as "noise." Disturbances caused by natural sources other than vibrations caused by nearby wind are generally known as microseisms, although strictly speaking all ground vibrations not associated with earthquakes, regardless of source, are microseisms. Microseisms (in the restrictive sense) have been put to practical use, as in attempts to apply them to hurricane sensing. More often they are a nuisance and seriously interfere with optimum recording of seismic waves originating from earthquakes.

It is background noise, whatever the source, that limits the maximum sensitivity at which a seismograph can be operated. In this discussion two types of background noise which interfere with optimum recording by short-period seismographs will be considered.

2.1. CAUSES OF BACKGROUND NOISE

2.1.1. MICROSEISMS. Microseisms (in the restrictive sense) have periods of 1 to 10 seconds. Longer periods have been noted, but long-period microseisms do not seriously interfere with the operation of a short-period seismograph and will not be considered here.

The literature abounds with papers on microseisms, their causes and propagation [6-14]. It is generally agreed that they originate from large bodies of water; that they are somehow associated with storms at sea and with fronts moving from sea to land or from land to sea or with other offshore weather conditions; and that they are coherent elastic waves, probably surface waves.

2.1.1.1. The Longuet-Higgens Theory. The mechanism of the origin is subject to considerable controversy. The theory which probably has the widest acceptance was formulated by Longuet-Higgens [9] which for maximum generation of microseisms requires that ocean swells having the same frequency move in opposite directions. Standing waves are thereby produced from which a second-order effect, in phase over a large area, causes fluctuating pressures on the sea bottom having twice the frequency of the individual waves. This theory is strengthened by the observation that microseismic peaks lag behind the closest approach of a storm or the peak intensity of a storm by as much as 48 hours [7]. This lag is the time required for the swells generated by the storm to reach a so-called "generating area" near the continent. Further, the microseismic frequency is often twice that of the oncoming swells.

2.1.1.2. Microseism Propagation Patterns. Determination of the source mechanisms of microseisms, aside from the observation that they are connected with large bodies of water, is more or less academic from the standpoint of optimum seismographic registration. The propagation patterns are not. Microseisms originating on the coast of Norway have been traced by Gutenberg across Eurasia as far as Irkutsk, more than 5,000 km away [10]. In North America, on 31 October 1952, 5-second microseisms throughout the central states, strong enough to almost nullify the usefulness of the short-period seismograph at Fayetteville, Arkansas, were traced to a storm in the Arctic Ocean, 5,000 km north of Fayetteville. Seven-second microseisms originating off the coast of Labrador have been traced 5,000 km to Pasadena on the West Coast [11]; 9-second microseisms originating off the coast of Alaska have been traced a like distance to the East Coast [12], and, under extreme conditions, as far as Bermuda and Puerto Rico [13], a distance of 6,000 to 7,000 km which includes 1,200 and 2,000 km of oceanic path, respectively.

The following observations have thus far been made:

(1) 2-second microseisms originating in the Great Lakes have been traced by Lynch 700 km southward into the Carolinas [14].

(2) 4- to 5-second microseisms have been traced as far as 5,000 km, across central and eastern North America.

(3) Microseisms having periods less than 4 or 5 seconds do not in general travel great distances across the western cordillera.

(4) 6 to 10-second microseisms travel from coast to coast. However, attenuation is much greater across the cordillera or the western Atlantic than across the plains.

(5) Earth filtering is more effective for the shorter-period microseisms. This may be one explanation for an observation that the period increases with distance. However, if real, this increase probably occurs over the first few hundred kilometers of travel, for microseisms attributed to West Coast or East Coast origins have the same periods in the distance range from 1,000 to 5,000 km [12].

Seismological networks in the United States have been greatly enlarged during the past few years, so that material for more detailed studies of microseismic phenomena is now available.

2.1.2. SHORT-PERIOD DISTURBANCES (PERIODS LESS THAN 2 SECONDS). Background noise in this category is generally local and rarely regional in origin, it may be coherent or apparently noncoherent, and it may have natural or artificial causes. Natural causes are:

(1) Surf breaking on a nearby shore or short choppy wave action near the shore.

(2) Weather action over small bodies of water. Causative mechanisms here are probably the same as with large bodies of water, but in miniature—or the same as (1) above. Background observations near Duluth, Minnesota, in late October and early November 1952, illustrate this point. A Benioff MC seismograph was temporarily installed on a gabbro sill about 4 km from Lake Superior. Under storm conditions, the background noise was heavy but irregular. During periods of relative quiet between the storms, the background was heavier but more coherent, apparently following the pattern of microseisms from oceanic sources but with shorter periods. Lake Superior is not to be classed as a small body of water, but the point is brought out here for purposes of illustration. As another example, the old Pierce Ferry station which operated for a decade or so in northwestern Arizona was located 1 km, more or less, from an upper arm of Lake Mead, which may be considered a small body of water. The underground was loosely consolidated terrace gravel and silt, but in a remote area. During periods of quiet, the background was relatively low. It was relatively high at the time of the usual afternoon winds. This condition was probably due in part to the wind disturbing the terrace upon which the instrument was located.

(3) Eddies produced by wind blowing over nearby objects such as hillocks, rocks, trees, fences, buildings, and other irregularities. Figure 1, taken from a VESIAC report [15], illustrates this point. This effect is greatly reduced if the source of the disturbance

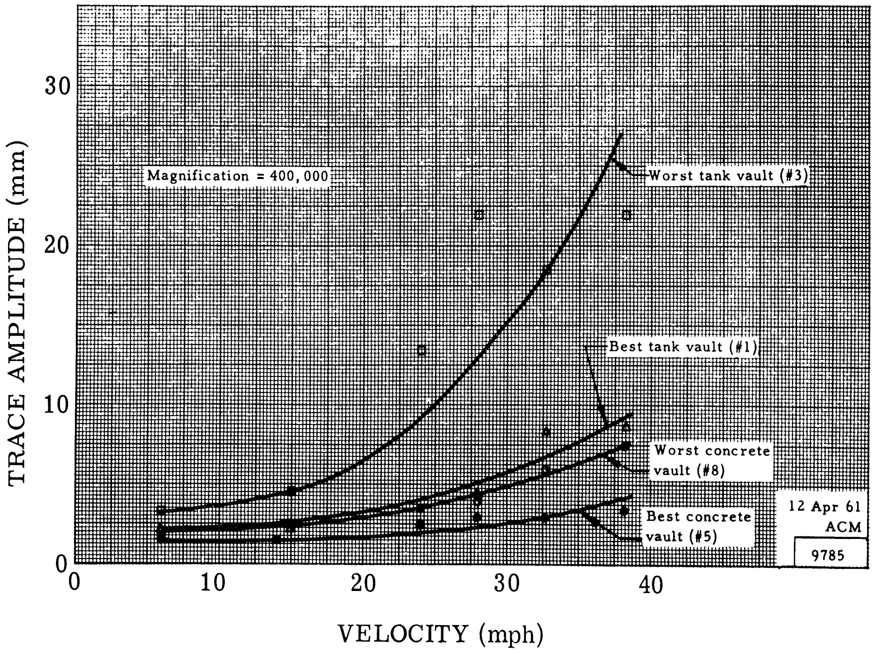

FIGURE 1. WIND NOISE AS A FUNCTION OF WIND VELOCITY FOR THE BEST AND WORST TANK VAULTS AT WMO [15]

is on alluvium and the seismograph is on bedrock, and if the ground above the seismometer vault is streamlined.

(4) Running water, rapids, and waterfalls. This applies likewise to dam spillways. The Bureau of Reclamation briefly operated a seismograph at a site located on a granite knoll 1.6 km south of Grand Coulee Dam. During periods of low water the seismograph was operated at high sensitivity, but during periods of high water noise with a period of 0.5 to 0.9 sec, resulting from falling water at the spillway, was great enough to almost nullify the effectiveness of the seismograph. A ground survey indicated that this noise attenuated about linearly in a northerly direction as far as 20 km from the dam.

Artificial sources of background noise include for the most part moving objects such as traffic and vibrating machinery. Man-made objects such as structures vibrating in the wind are considered natural sources. Artificial sources include:

(5) Reciprocating power plant and other machinery such as rock crushing, mining, and oil field machinery. This subject was covered in earlier publications [16, 17]. To summarize some important artificial noise characteristics:

(a) A continuous 3-cps vibration having amplitudes from 0.2 to 3 μ was observed in and near Long Beach, California. It was observed that oil field machinery give the same frequency, and that the vibrations attenuated with distance away from active oil fields.

(b) A large building vibrator operating on the thirteenth floor of a monolithic type reinforced concrete warehouse having a rectangular cross section caused the building to go into resonance when the machine period was that of the building. The building was coupled to the ground, which was dry and hard after nine rainless months, by means of skin contact and concrete piers. When the building was being forced into vibration in an E-W direction (along its long axis), resonance occurred at 0.50 second, the natural period of the building. Forced vibrations of the building were transmitted to the nearby ground and were observed by a seismograph. Compressional vibrations died out rapidly to less than $0.2\ \mu$ 200 meters west of the building (see Figures 2 and 3).

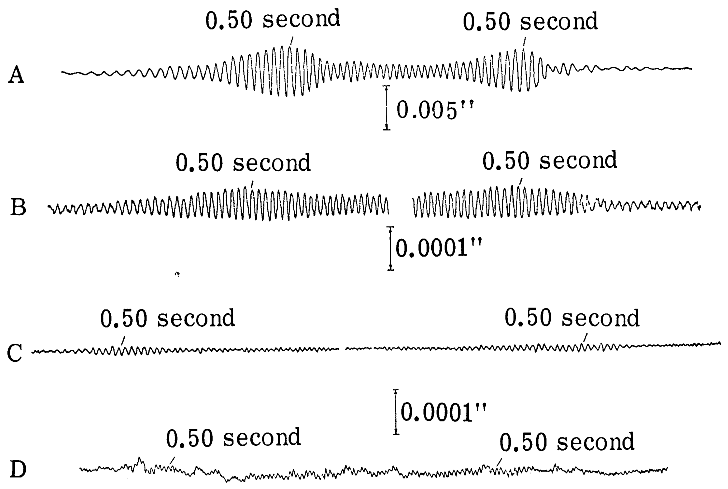

FIGURE 2. VIBROGRAMS MADE WHILE THE VIBRATOR IS ALIGNED PARALLEL TO THE LONG AXIS OF THE HOLLYWOOD STORAGE COMPANY BUILDING AND BROUGHT FROM REST TO MAXIMUM SAFE SPEED AND ALLOWED TO COAST TO REST. The maxima represent the building in resonance with the vibrator. The minimum between the maxima shows response to highest speed and therefore the greatest imbalance during a given test, but with the building out of resonance. Tests were made (a) on the thirteenth floor of the building; (b) on the ground 112 feet west of the building; (c) on the ground 0.6 mile south of the building; and (d) on the ground 1.2 miles south of the building. A passing pedestrian caused the irregularities of the trace in test d.

Shear vibrations having the same amplitude, $0.2\ \mu$, were carried 10 times as far, to nearly 2 km south of the building. After a heavy rain a few days later, forced vibrations in the building were not noted on the nearby ground.

(c) Early in 1942, a portion of the downtown area in Salt Lake City was served by power generators driven by two reciprocating steam engines. While one engine was in

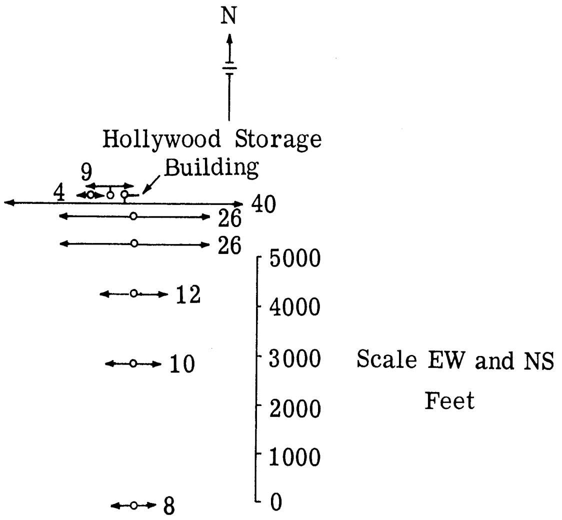

FIGURE 3. AMPLITUDES IN INCHES x 10^{-6} ON THE GROUND NEAR THE HOLLYWOOD STORAGE BUILDING WHILE THE VIBRATOR WAS ROTATING IN RESONANCE WITH THE BUILDING, PERIOD 0.50 SECOND

operation, vibrations in the nearby ground or in basements were measured. The orbit of ground motion was found to be an ellipse, the major axis of which was always normal to the direction of the source; this indicates transverse or shearing motion (see Figure 4). At a distance of 220 meters from the machine in line with its motion, transverse ground motion having a period of 0.31 second had an amplitude of 0.5 μ. At the same distance normal to this direction the amplitude (parallel to the forcing motion) was 2 μ; this again emphasized the preponderance of shear components in coherent noise transmitted in rigid ground.

(d) A coherent 2-cps disturbance was noted on most of the seismograph records [16] during Project COWBOY experiments in Louisiana, December 1959 to March 1960. The noise was believed to originate from pipeline pumps in the area, which had a frequency of 120 rpm.

(e) The seismograph at Tucson, Arizona, is disturbed by a rock crusher 1.6 km away. This noise disappears during the noon hour, at night, and on Sundays and holidays (see Figure 5).

(6) Vibrations from traffic. This noise is really in the same category as (5). However, noise from traffic is less coherent than that from reciprocating machinery because of the mobile nature of the sources. Trains are probably the greatest offenders; disturbances from them carry to distances of 16 km or more.

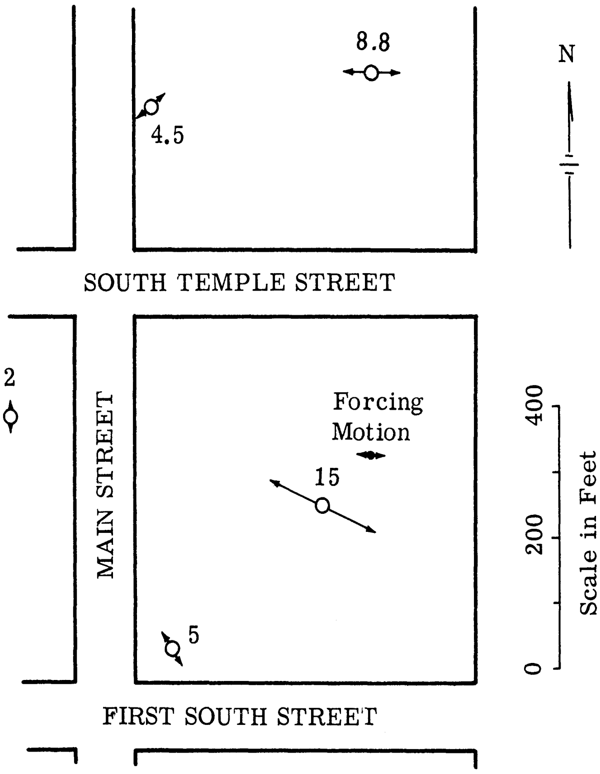

FIGURE 4. GROUND PLOT OF AMPLITUDES OF MAJOR AXIS OF GROUND VIBRATIONS REPRESENTED BY VECTORS, FORCED BY POWER-PLANT MACHINERY, SALT LAKE CITY. Numerals represent amplitude in inches x 10^{-5}, forcing motion one machine only.

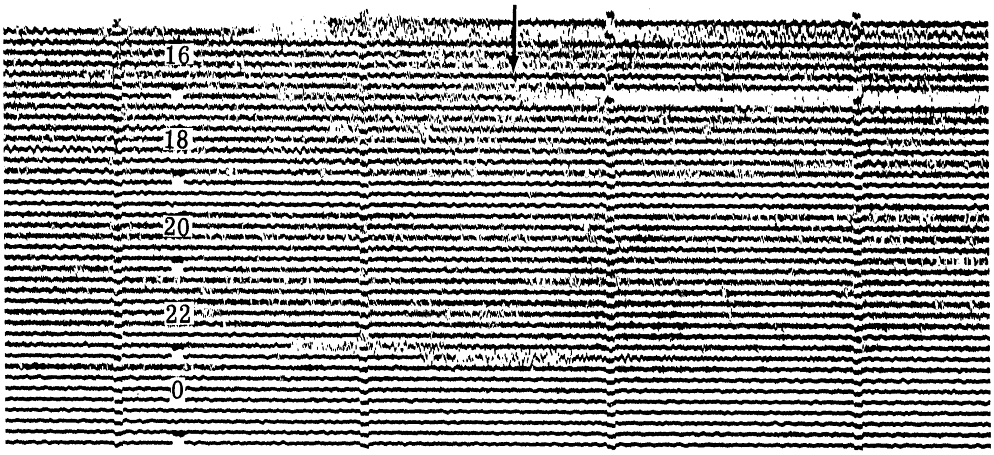

FIGURE 5. SECTION OF A SEISMOGRAM FROM THE TUCSON STATION, SHOWING STRONG NOISE GENERATED BY A ROCK CRUSHER

2.2. INFLUENCE OF GEOLOGIC ENVIRONMENT

The geologic environments of the noise source, of the location of the station, and of the intervening area have much to do with the efficiency of a seismograph station. Unweathered granite has generally been considered the best underground for a station. Quartzite, limestone, or basalt, if not underlain by inferior rock, should serve equally well, with certain exceptions which among other things will now be considered.

(1) If the noise source and the station are on the same formation, disturbance at the station will be relatively great. If the formation is rock, the noise presumably is transmitted for the most part by shear, as mentioned earlier, or less likely as Rayleigh waves. If the rock is granite, or homogeneous with depth, the shearing motion, if represented as body waves, would be expected to spread out in spherical waves, and attenuation would be relatively large. If the formation is a low-speed layer, however, noise would be channeled in the layer. Further, if there is a low-speed layer near the formation, there may be leakage from that layer and noise attenuation will be relatively low. That is a probable reason why a granite outcrop may be superior to limestone or basalt, unless they are upturned. Note: Noise caused by the impact of falling water over Grand Coulee Dam reached a seismograph on granite 1.6 km south of the dam, probably in the form of Rayleigh or SV waves, because by far the largest amplitudes (of 0.5- to 0.9-second noise) were on the vertical and radial components. A body of water 100 meters deep lay in between.

In a relatively non-rigid formation such as unconsolidated or water-saturated alluvium, noise is probably transmitted as Rayleigh waves, by reflection between interfaces, or by other means, but not primarily by shear. Seismic signals recorded by stations on alluvium are relatively large, but noise from local sources is larger, reducing the station efficiency.

Where the noise source and the station are on different formations, disturbance at the station may be relatively light, especially if the formations have widely different acoustic properties. For example, if the station is on a basement rock and the noise source is on nearby alluvium, or if the source is on rock and a discontinuity consisting of alluvium, till, or other unconsolidated material lies between, the unconsolidated material will serve as a damper. As an example, the College, Alaska, station lies on residuum of a schist hill. Train noise disturbs the seismograph more when a train crosses an outcrop on the point of a hill about 1.5 km distant than when it passes on valley fill within 0.5 km of the station.

A number of surveys have been made in the past few years. Figure 6 is a plot of noise spectra at various sites in the United States made by the Geotechnical Corporation [15]. This study covers the period range from 0.2 to 5.0 seconds, since this includes the range which disturbs a short-period seismograph. Figure 7 shows the results of a similar survey made by The University of Michigan [18].

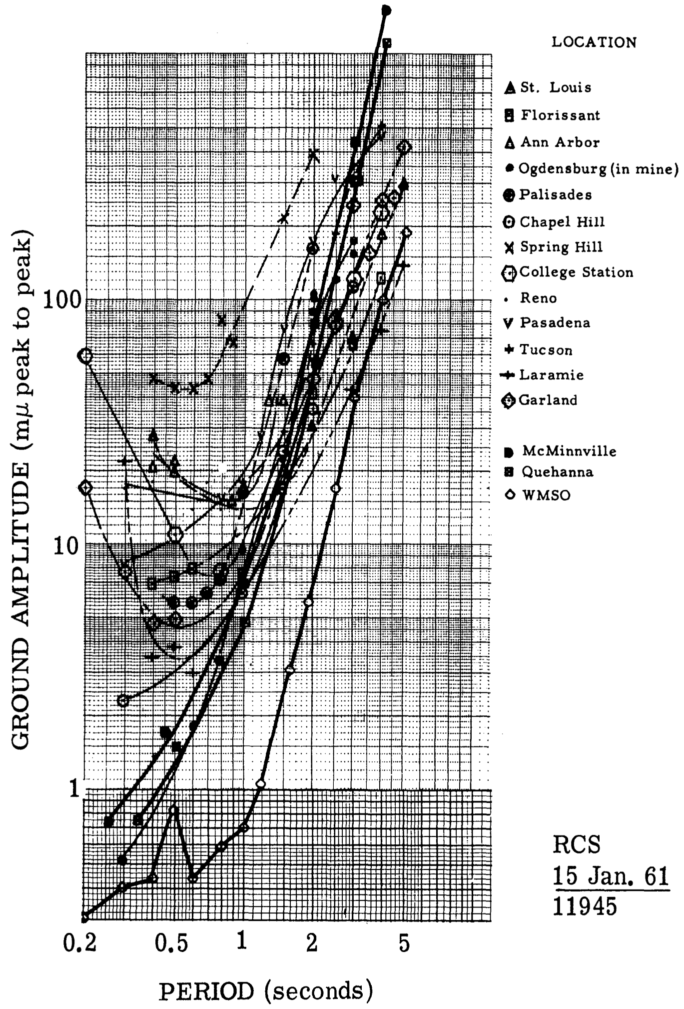

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FIGURE 6. NOISE SPECTRA AT VARIOUS SITES IN THE UNITED STATES [15]

United ElectroDynamics, Inc. [19], has completed noise correlations with geologic and geographic environments along two profiles: (a) in the Pacific Northwest from the coast of Washington to the Wallowa mountains in northeast Oregon; (b) in the Pacific Southwest from the coast of California to Death Valley. In California, noise levels of periods ranging from 1.25 to 1.5 seconds were related to environment. In the northwest there was a definite correlation with the weather: noise came from the ocean during storms at sea, and from the north to west at other times. Figure 8 is a representation of average noise amplitudes at three locations along the northwest profile.

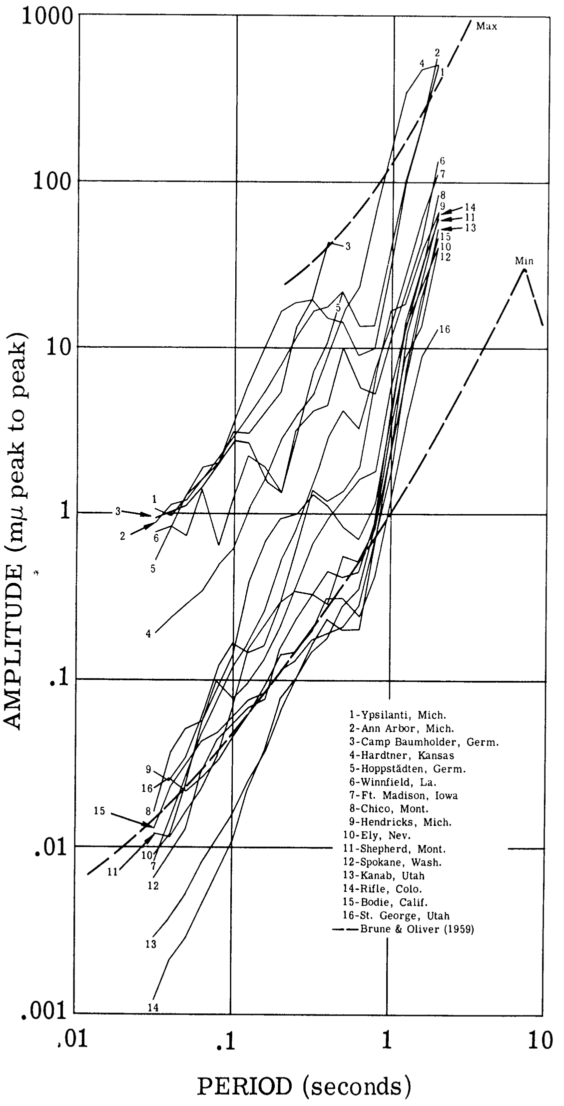

FIGURE 7. THE SPECTRA OF SEISMIC NOISE RECORDED AT 16 GEOGRAPHIC LOCATIONS. Data are normalized to 1-cps bandwidth [18].

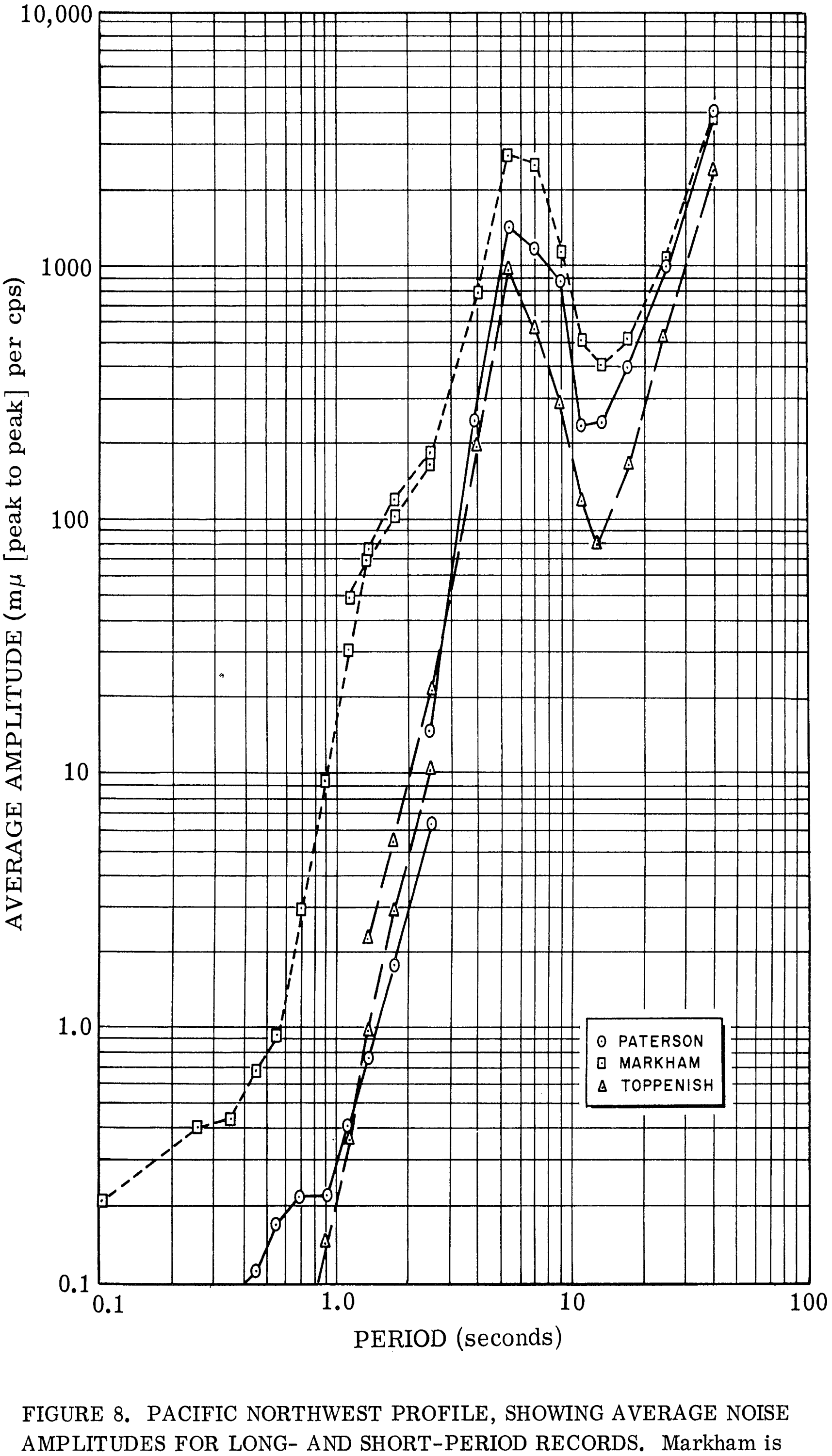

FIGURE 8. PACIFIC NORTHWEST PROFILE, SHOWING AVERAGE NOISE AMPLITUDES FOR LONG- AND SHORT-PERIOD RECORDS. Markham is on the coast of Washington, Toppenish is in south central Washington, and Paterson is about 90 km ESE of Toppenish [19].

2.3. REDUCTION OF NOISE EFFECTS

Reduced noise load can be attained two ways: (a) by choosing a locality where the noise is relatively low, or (b) by the use of filters to reduce undesirable noise while maintaining or augmenting the strength of the signal. These methods presuppose that the noise at the source is not reduced.

2.3.1. LOCALITIES WHERE THE NOISE IS RELATIVELY LOW

2.3.1.1. Geographic Localities. An optimum site for a seismograph station would naturally be one which is remote from noise generators and has a natural filter lying between the chief noise source and the site. This would be a locality on the interior of a continent, "shaded" from the ocean by at least one and preferably two mountain ranges, and remote from lakes, cities, railroads, and other noise sources. The Blue Mountain Seismological Observatory in northeastern Oregon, near Baker, is an example of a quiet 10-element array station; it will be described later. Reservoirs to be formed by present and future dams in the Snake River Canyon are more than 35 km from the site and probably will not cause serious disturbances.

The seismograph stations described here can be operated at high gain because of a relatively low background. The instrumentation at these stations is described in a later section. The accompanying initials are the C&GS station abbreviations [20].

Eureka, Nevada (EUR). This station, located in the Great Basin province 600 km from the Pacific Ocean and in the shadow of several mountain ranges and alluvial valleys, has earthquake recording capabilities equal to those of the best stations of the Americas. It may be described as a "shoestring" station because of its low initial cost and because it operates only a short-period vertical seismometer. The seismometer, a Benioff MC model, is located a hundred or so meters within the adit of an abandoned mine. It drives a 0.5-second Lehner-Griffith recording galvanometer located in a small building outside the mine. The maximum gain for 1.0-second period ground motion is about 450,000, but this would probably not be attained during autumn and winter, since the 5-second microseisms from trace to trace often overlap. Neither mining operations, traffic on U. S. Highway 50, nor activity in the nearby town 2 to 3 km from the station disturbs the seismograph materially.

Albuquerque, New Mexico (ALQ). This station is a unit of the Coast and Geodetic Survey World-Wide Standardized net, described in Section 4.1.2, and is a part of the Survey's seismological laboratory. The seismograph vault is a tunnel driven 20 meters into a granite knoll. The city of Albuquerque, the Santa Fe railroad, the airport, and other artificial noise sources are all 20 to 30 km north and west of the station and are for the most part on desert valley fill.

The instruments apparently are not materially disturbed by any artificial source except occasional blasts on a nearby military base. The short-period instruments operate at a gain of about 400,000 during the summer, and at 200,000 during the winter because of ocean-generated microseisms. This site was chosen after an exhaustive background-noise survey. Its choice was governed in part by the convenience to facilities that a city affords. Sites east of the cordillera were rejected, largely because of the prevalence of a 2-cps background noise.

Shillong, India (SHL). The station is located on bedrock in the mountainous area between the Bay of Bengal and the Brahmputra Valley. The city of Shillong is located in a hilly country 2 to 3 km from the station and 100 meters lower in elevation. Industrial noise sources appear to be inconsequential. The entire area is shielded from microseismic sources from the north by the Himalaya Mountains, and the station is not materially disturbed by ocean-generated microseisms except during monsoon seasons and during occasional hurricanes. Until April 1963 gain settings had been somewhat below the microseismic level, so that the true capabilities of the station had not been realized. This condition was alleviated after installation of World-Wide Standardized instruments in April 1963.

Tamanrasset, Algeria (TAM). This station is located in the Sahara desert 1700 to 2500 km from the Atlantic ocean and 1400 km from the Mediterranean sea. Culture noise is insignificant. Local winds, however, disturb the short-period seismographs about the same as at any other station. The amplitudes of residual noise having periods of 2.5 to 3.5 seconds are from 10 to 50 times lower than the amplitudes of similar noise at the European stations. Rocard [21] attributes this residual noise to diastrophism. He feels that because it is much lower at Tamanrasset than in Europe the Tamanrasset area is relatively stable geologically. It would seem, however, that the great distance from ocean-generated microseism sources would be a more tenable explanation. Because of its location on the interior of a large continent, this station can be operated at high gain.

South Pole, Antarctica (SPA). This station originated as a part of the IGY program, and its continuation is made possible as a result of the IGC. Before its installation, some concern was raised (a concern not shared by this writer) that the station would be ineffective because of the 3,000-meter ice overburden above bedrock. In actuality, bedrock is fairly close to the surface because natural ice is, by definition, a rock. A Benioff MC short-period vertical and two Wilson-Lamison 4-second horizontal seismometers were located in a vault reached by a tunnel 400 meters long. The vertical instrument operated a 0.5-second Lehner-Griffith galvanometer, and the horizontal seismometers operated 4-second galvanometers, all located at a recording station near the living quarters. Early in the history of the station, considerable shut-down time was experienced because of broken galvanometers and other failures caused by environmental difficulties. During the past few years, however, operation has been very satisfactory, and culture and wind-induced background noise is remarkably low. Contrary to expectations, ocean-induced microseisms are also quite low, perhaps because there are structural discontinuities between the central plateau and the coast and because the ice cap has high absorption coefficients for short-period surface waves. The South Pole and other Antarctic seismograph stations are of high value because they afford a southern control useful in monitoring earthquakes in the southern hemisphere. A World-Wide Standard seismograph has now been installed at the South Pole station.

Quetta, Pakistan (QUE). The site is geographically ideal. The Arabian Sea is 550 km to the south, and in every other direction lies the vast continent of Eurasia with its shielding mountain ranges. The city of Quetta is located near the center of an elevated intermountain valley on valley sediment of unknown depth. The geophysical observatory is located near the edge of this valley, within a few hundred meters of a steep mountain slope. A World-Wide Standard seismograph is installed in a room adjoining the observatory. At the time of writing, the gain of the short-period vertical was about 200,000. From an inspection of available records, ocean-generated microseisms are very low, but high-frequency background noise disturbs the short-period records. It is believed that this noise is largely cultural. According to station descriptions, the short-period seismometers are located near the observatory building. An outpost station on nearby solid rock may materially reduce the noise.

2.3.2. THE OUTPOST STATION AND TELEMETRY. An outpost station is defined as one in which ground motion is sensed or picked up in a seismically favorable but relatively inaccessible locality and recorded at an accessible but seismically unfavorable locality. Several ways of doing this are now in use.

(1) The seismometer can be located on a rock outcrop or other favorable environment away from traffic, and the recorder at a more convenient location; there is no amplification between the seismometer and the recording galvanometer. The College, Alaska, outpost station is probably an outstanding example of this. A Benioff MC vertical seismometer is located in an underground pit on a schist hill about 4 km from the main station. The recorder is located at the main station (the C&GS College Magnetic and Seismological Observatory), and the interconnection is a 4- to 4.5-km length of spiral-4 cable, a product of the U. S. Army Signal Corps. The long line in Alaska is possible because atmospheric disturbances such as lightning storms are almost nil in the area. Elsewhere—in Fayetteville, Arkansas, for example—it was found that electrical induction in a 150-meter connecting line was excessive during an electric storm.

Many other stations with a relatively short seismometer-to-galvanometer connection, Eureka, Nevada, for example, are now in operation; other stations could probably be improved by using this method.

(2) When the seismometer site is too remote to be linked to the recording station without amplification, the seismometer signal can be amplified and is telemetered to the recorder over a wire linkage. The possibilities of this method are continent-wide wherever hard-wire telephone service is available. The Berkeley, California, telemetering network (see Figure 9) is a good

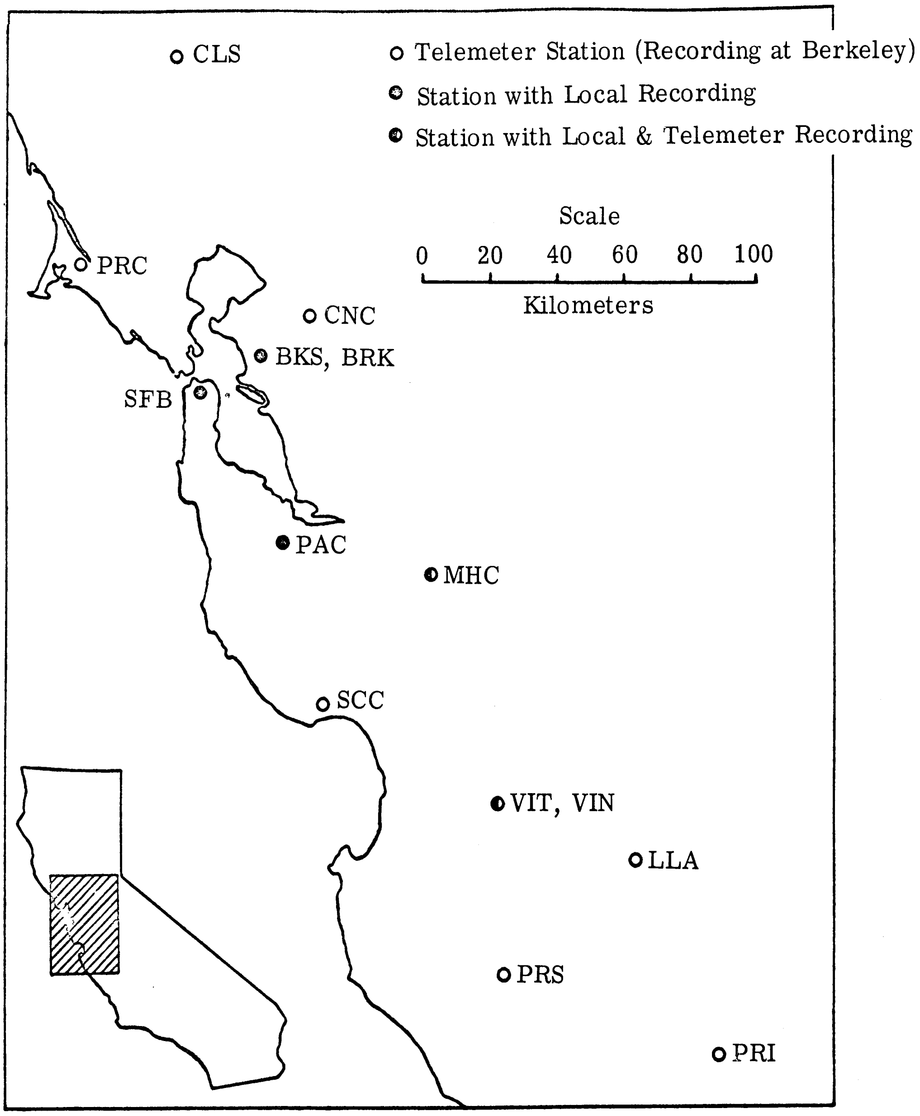

FIGURE 9. CENTRAL CALIFORNIA SEISMOGRAPHIC NETWORK, UNIVERSITY OF CALIFORNIA. BKS—Berkeley (Strawberry). BRK—Berkeley (Haviland). CLS—Calistoga. CNC—Concord. LLA—Llanada. MHC—Mt. Hamilton. PAC—Palo Alto. PRC—Point Reyes. PRI—Priest. PRS—Paraiso. SCC—Santa Cruz. SFB—San Francisco. VIN—Vineyard. VIT—Vineyard telemeter.

example. Ten Benioff VR vertical seismographs are located along the central California fault systems. The ones farthest from Berkeley are 180 km SE and 85 km NNW. All are connected to the University of California's central recording station at Berkeley by communication channels leased from the telephone company. Recording is on a Geotech Develocorder, described in Section 3.2.2, with check recordings on Helicorders. These facilities make possible immediate recognition of earthquakes along central California's fault systems, and on the azimuth of distant earthquakes. Schematic diagrams of the central California telemetering network are shown in Figures 10 and 11.

An operating example of an outpost station with which telemetry is used is a station in Tasmania. A 1000-meter high plateau near the center of the island, with moderate to heavy rainfall, provides a natural resource in the form of hydroelectric energy. Because certain power facilities cross ground which may be seismically active, the Tasmanian Hydroelectric Authority cooperated with the University of Tasmania to establish a net of seismograph stations on the island. This net uses a combination of wire and radio linkage in its telemetering system. Two units of a tripartite net located around the center of the island are in line of sight with the top of Mt. Wellington, a 1270-meter high peak near Hobart. The third is in line of sight with

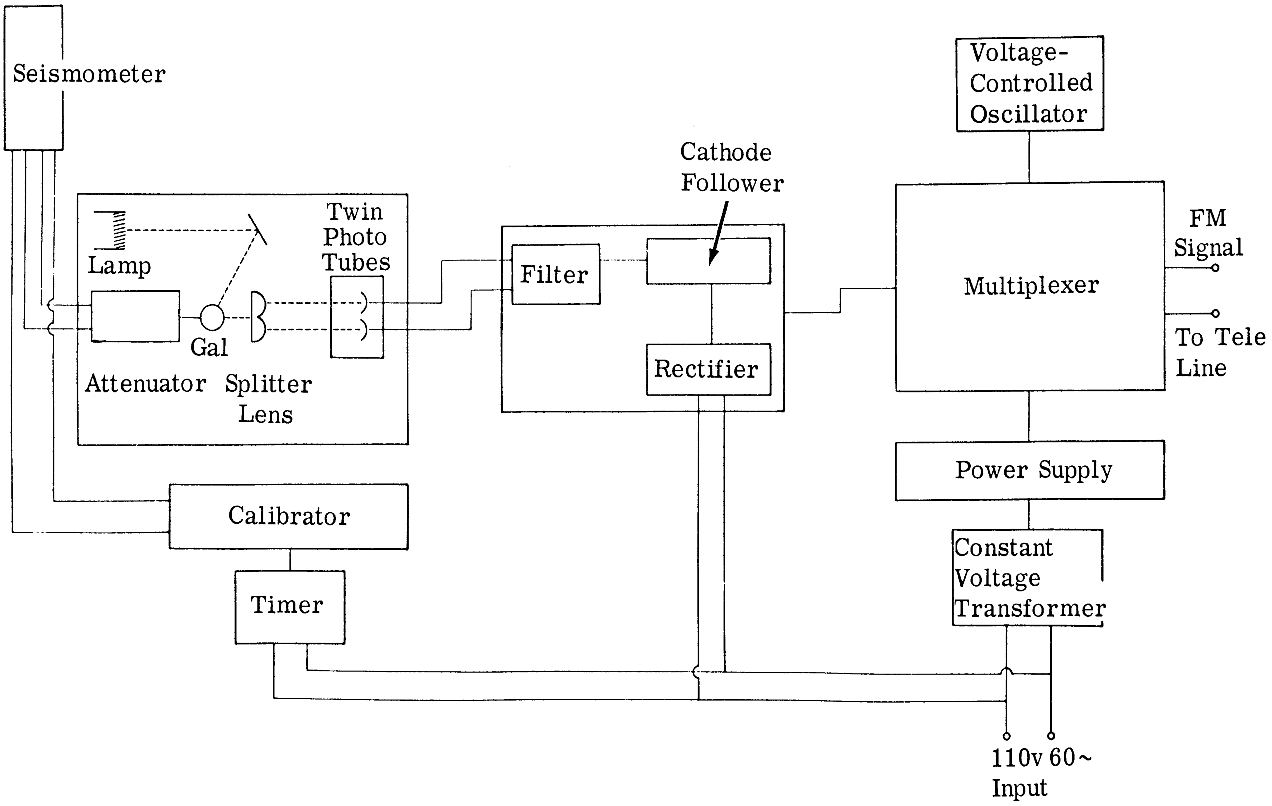

FIGURE 10. SEISMIC TELEMETER EQUIPMENT FOR OUTSTATIONS IN THE CENTRAL CALIFORNIA NETWORK

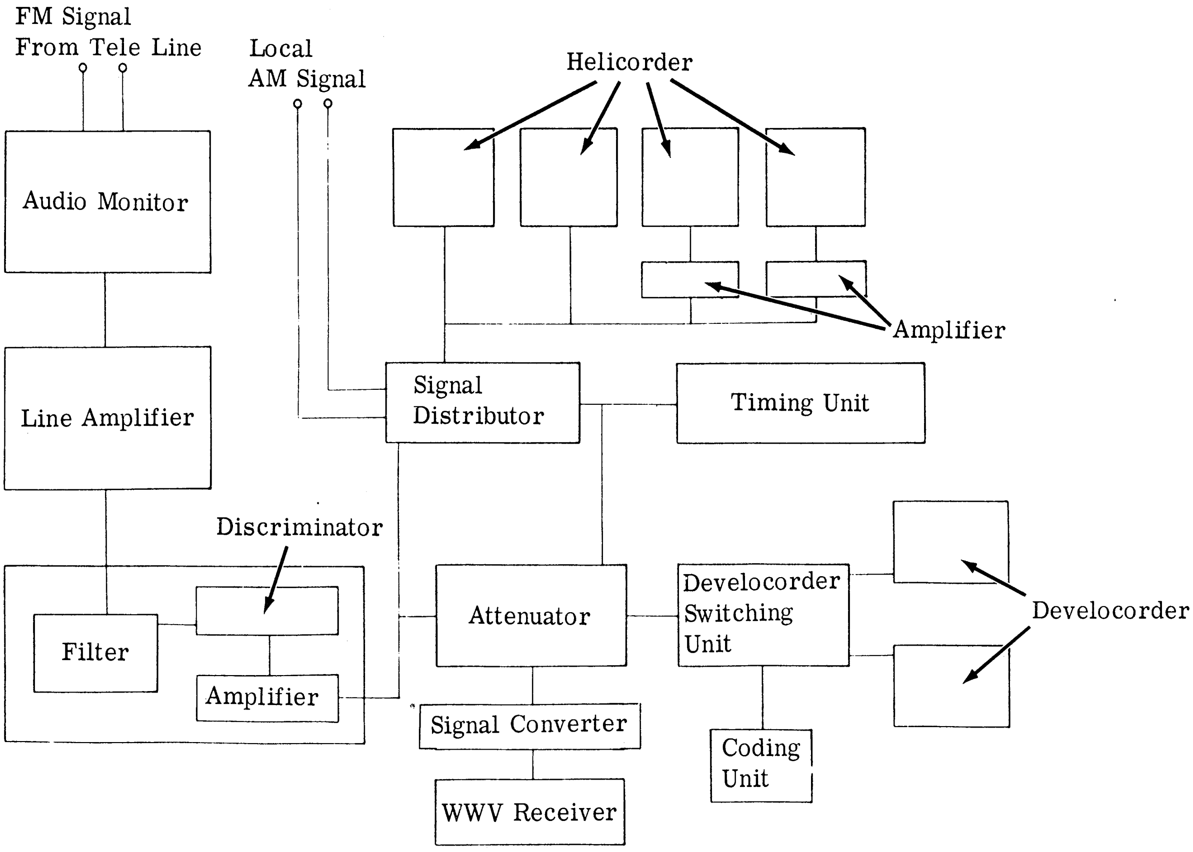

FIGURE 11. TELEMETER RECEIVING CONSOLE, CENTRAL CALIFORNIA NETWORK

Mt. Barrow, on which is located a television relay station and which is in line of sight with Mt. Wellington. Seismic signals are telemetered to Mt. Wellington, or are relayed there by radio from Mt. Barrow, and then carried over a land line to the university at Hobart; there they are recorded side by side with signals from a local station.

(3) If the seismometer-to-recorder distance is fairly long and the seismometer relatively inaccessible, the communication channel can include a radio link. This system has been in use with varied success in Canada and South Africa. In the United States the method was first successfully used in Tucson, Arizona. The seismograph station there includes a Benioff VR vertical, one of the first to be placed in service. In its early history, the station, located on caliche, a part of the valley fill, was considered the best in the United States. However, a rock crusher located 1.5 km more or less from the station, and other noises associated with the expanding city, rendered weekday daytime short-period registration ineffective. In 1957, a telemetering system, using a radio link, was perfected and placed in service. A Benioff MC vertical seis-

mometer was located in a rock outcrop near the summit of Mt. Lemmon, about 10 km northeast of the observatory. The transmitting station with its antenna was about 150 meters distant, and the top of the antenna was on line of site with the receiving antenna at the observatory. As with the wire-linked telemetering system, the signal was amplified at the transmitter by a photo-electric split beam cathode ray follower. A block diagram of the system is reproduced in Figure 12. The new world-wide station is located at a relatively quiet spot 9 or 10 km from the old one; the telemeter has been discontinued.

This section has shown that telemetry provides remote recording from a seismically favorable but inaccessible location, and also a means of recording the output from an entire net of stations on a single tape. The subsections to follow describe varieties of telemetering systems for use by really inaccessible outpost stations.

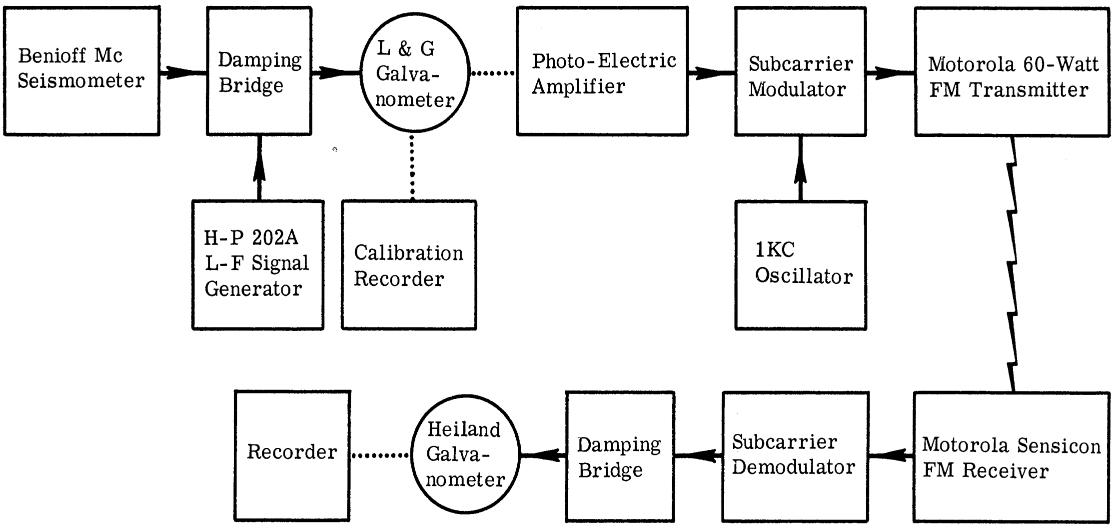

FIGURE 12. TELEMETERING SYSTEM AT TUCSON

2.3.3. DEEP-HOLE SEISMOMETRY. One means of escaping from noise is to go deep underground.

It will be assumed that background noise is surface generated. If it is in the form of Rayleigh waves, by theory the rate of attenuation of vertical motion with depth would be 5 db for the first half wavelength of depth and 10 db for each increment of half a wavelength thereafter. Consequently, attenuation with depth would be greatest for the higher-frequency vibrations and in unconsolidated sediments. This reasoning is prevalent in current literature and panel discussions on attenuation of background noise with depth. Little if any thought has been given to the possibility that culture and wind noise may in large part be S waves and that attenuation with depth may be a result of absorption and of inhomogeneities of the rock between the surface and the detector in the bottom of a well.

The following subsections describe several experiments with deep-hole seismometry.

2.3.3.1. The Homestake Mine, Lead, South Dakota. A pioneering experiment in deep-hole seismometry was performed by the Coast and Geodetic Survey in this mine. In April 1950 two Benioff MC vertical seismographs were operated side by side on the lowest level, 5,000 feet (1.5 km) beneath the surface, and set to give identical responses. One was then moved to the surface, and both were operated for several weeks. This experiment was repeated on a more elaborate scale in March-June 1953, when one Benioff VR vertical was operated on the 5,000-foot level and another on the 300-foot level. Signals from both instruments were telemetered over hard wire to a film recorder on the surface. Provision was made to filter out noise having frequencies of 5 cps or greater; this gave an element of unreality to signals from blasts in the mine. From the two series of tests, the following observations were made:

(a) Ocean-generated microseisms having periods of 4 seconds or greater were not attenuated with depth.

(b) Culture-generated noise having periods of 1 second or less caused by traffic and machinery, was attenuated with depth by a factor of at least 10.

(c) Noise from operations in the mine disturbed the seismograph on work days.

(d) P waves from distant earthquakes having periods of 1 second or less, as recorded on the surface, have an average ratio of 2/1 to those recorded on the 5000-foot level of the mine; this is in accordance with theory.

Because of difficulties in operation and the prevalence of machinery-generated noise, the Homestake mine was not considered a suitable site for a permanent station.

2.3.3.2. Exotic Environments

2.3.3.2.1. Deep-Hole Seismographs. Deep-hole seismographs have been developed under contract by the Geotechnical Corporation and United ElectroDynamics, Incorporated. Experiments (a) and (b) were conducted by Geotech.

(a) Grapevine, Texas. During the summer of 1962 one seismometer was installed at the bottom of a deep well at Grapevine, Texas, depth 3100 meters (10,150 feet); another in a shallow well, depth 23 meters; and the third, a small model Geotech seismometer, at the surface for comparison purposes [22]. Available test runs indicated that at 3100 meters a 3- to 4-cps noise was attenuated by a factor of 25 to 1. Early data indicated that the relative strength ratio between the surface signal and the signal at 3100 meters was somewhat less than the theoretical factor of 0.5, more nearly 0.3 to 0.4, and in an extreme case as low as 0.1. This may be because the surface material has lesser seismic wave speed, and hence associated amplitudes must be greater to maintain the same energy content. From this experiment it seems evident that the increase in signal-to-noise ratio with depth is from 2 to 8 times.

A later test, in November 1962 [23], indicated that signal strength at depth relative to that at the surface was somewhat more than 0.5 or nearly 1.0. If this finding is valid, the above explanation need not hold; at any rate, the finding introduces the possibility that the low strength of both signal and noise at depth in the early experiment was caused by poor coupling between the seismometer and the borehole.

(b) Hobart, Oklahoma. A test run was made in the Prater No. 1 well during the late summer of 1962. The well has about the same depth as that at Grapevine. A nearby well 158 meters (512 feet) deep was tested simultaneously with the seismometer in the deep hole and with one on the surface. It was found that the S/N in the shallow well was about 3/1. In the bottom of the deep well it was slightly less than this, although at 5,000 feet it was slightly better than 3/1. This test may not be valid; escaping gas in the deep well may have added to the noise level. Tests described here more or less confirm results of earlier tests by the Jersey Production Research Company [24].

(c) Tube noise and casing noise. Experiments were tried at the Hobart well and at some of the 3D wells, described later, on the transmission of noise down the casing. A noise pulse was induced into the casing by striking the top of the casing a sharp blow. It was found that that the speed of the seismic pulse down the hole was that of the tube noise, and not of the casing. It is believed that tube noise may have been partly responsible for the inefficiency of the Hobart well. Use of plugs or baffles in the well might have helped to reduce the noise level.

2.3.3.2.2. Ocean-Bottom Seismometry. This form of telemetering has great potential: more than half of the earth's surface is covered by oceanic areas more than 100 km from the nearest land. The Lamont Geological Observatory, the Scripps Institute of Oceanography, and the Texas Instrument Company are currently experimenting with ocean-bottom seismographs [25]. The seismographs have been constructed, and trial experiments have been made. Operational problems include power supply and data recovery. Atomic batteries, although currently expensive, appear to promise an effective power supply. Data can be recovered in several ways. One is to recover the seismograph after a period of operation; another is to telemeter seismic signals by wire to a surface recorder on a buoy or to a land-based recorder on an island. Results thus far indicate that the floor of the deep ocean is relatively quiet remote from land, but relatively noisy near land regardless of depth, and that the signal-to-noise ratio is nearly equal to that of land-based seismographs (see Figure 13).

Since ocean-bottom seismometry is very costly, it should be combined whenever possible with other oceanographic operations, such as deep sea tide and tsunami research. Furthermore, all possible advantage should be taken of abandoned telegraph cables.

2.3.3.2.3. Moon Seismometers. The Lamont Geological Observatory and the California Institute of Technology have constructed seismometers which will withstand impacts of falling on the moon and function thereafter as vibration detectors with capabilities of telemetering the signals to earth-based recorders. The one attempt thus far to land a seismometer on the moon has failed. These seismometers are relatively small, and they may provide instrumental capability in other inaccessible places, such as ocean bottoms or deep holes.

2.3.4. FILTERS

2.3.4.1. Frequency Filters. Undesirable frequencies may be reduced or almost eliminated by the proper use of bandpass filters. An electromagnetic earth-driven seismograph is a bandpass filter with gradual cut-offs on the two sides of the band. Electronic filters provide sharper cut-offs. Frequency filters, however, have certain undesirable qualities:

(1) They filter out signals that we often wish to investigate. This fault could be overcome by multi-recording a number of frequency bands; but to do so would add to the volume of already voluminous data. Alternatively, the broadest frequency band possible could be recorded on magnetic tape, and desirable frequencies could be investigated on playback.

(2) Filters, including electronic ones, distort the signal. In fact, any transfer of a seismic signal from one medium to another—say from the earth to a wiggly line on a film or paper, or from the earth to magnetic tape track and from the tape to a sheet of paper—results in some distortion. A major problem in seismology is to reproduce source conditions, or conditions along a ray, by the study of distorted images on films or sheets of paper.

(3) Quite often, the frequency of the signals we wish to study is that of the noise we wish to eliminate or reduce.

2.3.4.2. Wavelength Filters or Arrays. The effectiveness of a wavelength filter is based on an assumption that background noise is surface-generated and is more or less confined to low-speed surface layers, whereas a seismic wave from an earthquake travels at a higher speed

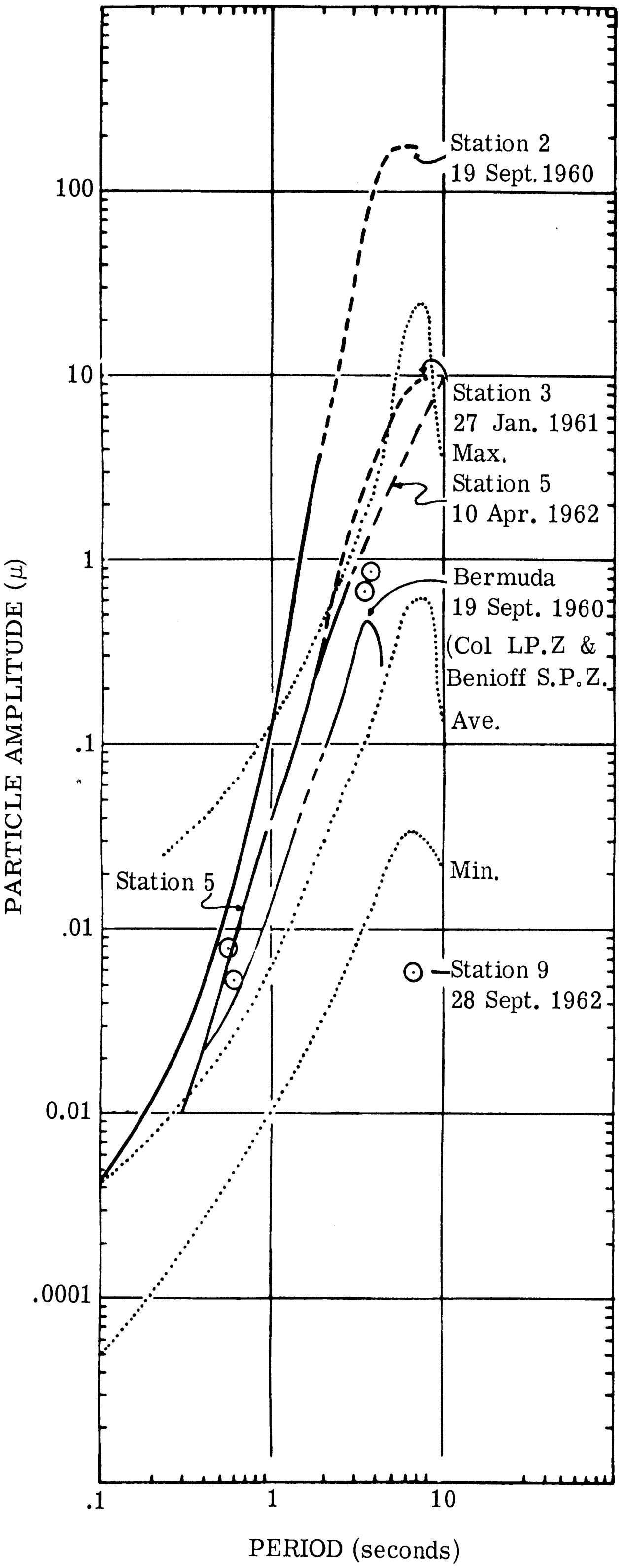

FIGURE 13. RESULTS OF OCEAN BOTTOM SEISMOMETRY. (a) Station 2 is about 140 n mi WSW of Bermuda; stations 5 and 9 are about 70 and 60 n mi south of Bermuda; and station 3 is in the Gulf of Mexico about 400 n mi south of New Orleans [25].

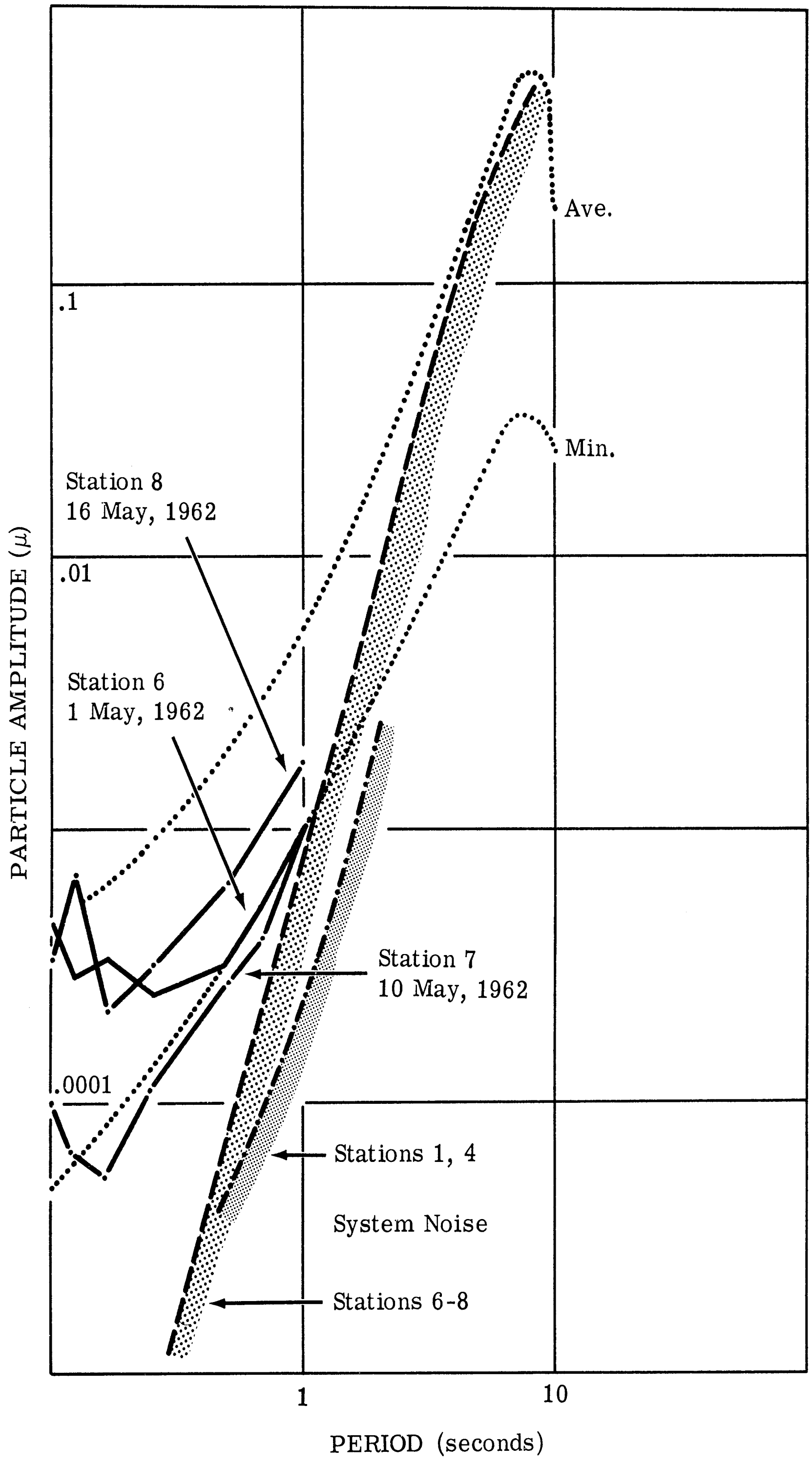

FIGURE 13. RESULTS OF OCEAN BOTTOM SEISMOMETRY. (b) Stations 6, 7, and 8 are in the Arctic near 81° north latitude and between 172° and 173° east longitude. Stations 1 and 4 are in the Atlantic near 72° west longitude and respectively near 35 1/2° and 25 1/2° north latitude [25].

and arrives from depth; hence a seismic wave of the same frequency has a greater wavelength than surface-propagated noise. If the seismic signal is a P wave from a regional or distant source, its apparent speed along the surface is from 7.8 to 25 km/sec, whereas the speed of noise is presumably no greater than 3 or 4 km/sec. Linear and cross arrays have been designed with the idea that dominant noise is noncoherent and will pass the array along its length and be phased out while the expected signal reaches one leg of the array broadside. The triangular array is a modification of this.

Mr. Leslie F. Bailey, of the Coast and Geodetic Survey, has designed an array which has not been demonstrated but which has possibilities of providing a greater depth of filtering, for noise arising from outside the array within certain frequency ranges. Preliminary work calls for testing an array site for the true phase velocity of the noise to be filtered.

Several limited-array observatories are now in operation, most of them under the technical supervision of the Air Force Technical Applications Center (AFTAC) as a part of Project VELA UNIFORM, which is under the overall direction of ARPA (Advanced Research Projects Agency). Two of these stations will be briefly described. They follow the pattern recommended by the Geneva Conference in 1958.

2.3.4.2.1. The Wichita Mountains Seismological Observatory (WMO). This observatory is located on granite basement about 25 km northwest of Lawton, Oklahoma [26]. This 10-element array is arranged in the pattern of an equilateral triangle, 4 elements on each side and one in the center, and the elements 1 km apart. The elements in the array are Johnson-Matheson vertical seismometers. Six of the elements are installed in tank vaults, each imbedded in concrete and buried under 2 feet of earth for insulation. The remaining elements are in concrete vaults which contain also Benioff short-period vertical and horizontal seismometers in addition to Sprengnether and Press-Ewing long- and intermediate-period seismometers. The output from each element of the array recorded is on a Develocorder at 400K gain, together with a WWV trace, a 4-unit summation, a 10-unit summation, N-S short-period (SP) ground motion, EW SP ground motion, and a low gain channel. Broadband and long-period recordings are recorded on another Develocorder; selected recordings are made on 1-inch wide magnetic tape operating at 0.3 ips.

2.3.4.2.2. Blue Mountain Seismological Observatory (BMO). This observatory is located on granite basement about 42 km east of Baker, Oregon, and about 4 km south of Sparta [27]. It is a 10-element array built after the same pattern as the WMO (see Figure 14). Each element is contained in a tank buried under 2 feet of earth, as at WMO. Near one of the elements

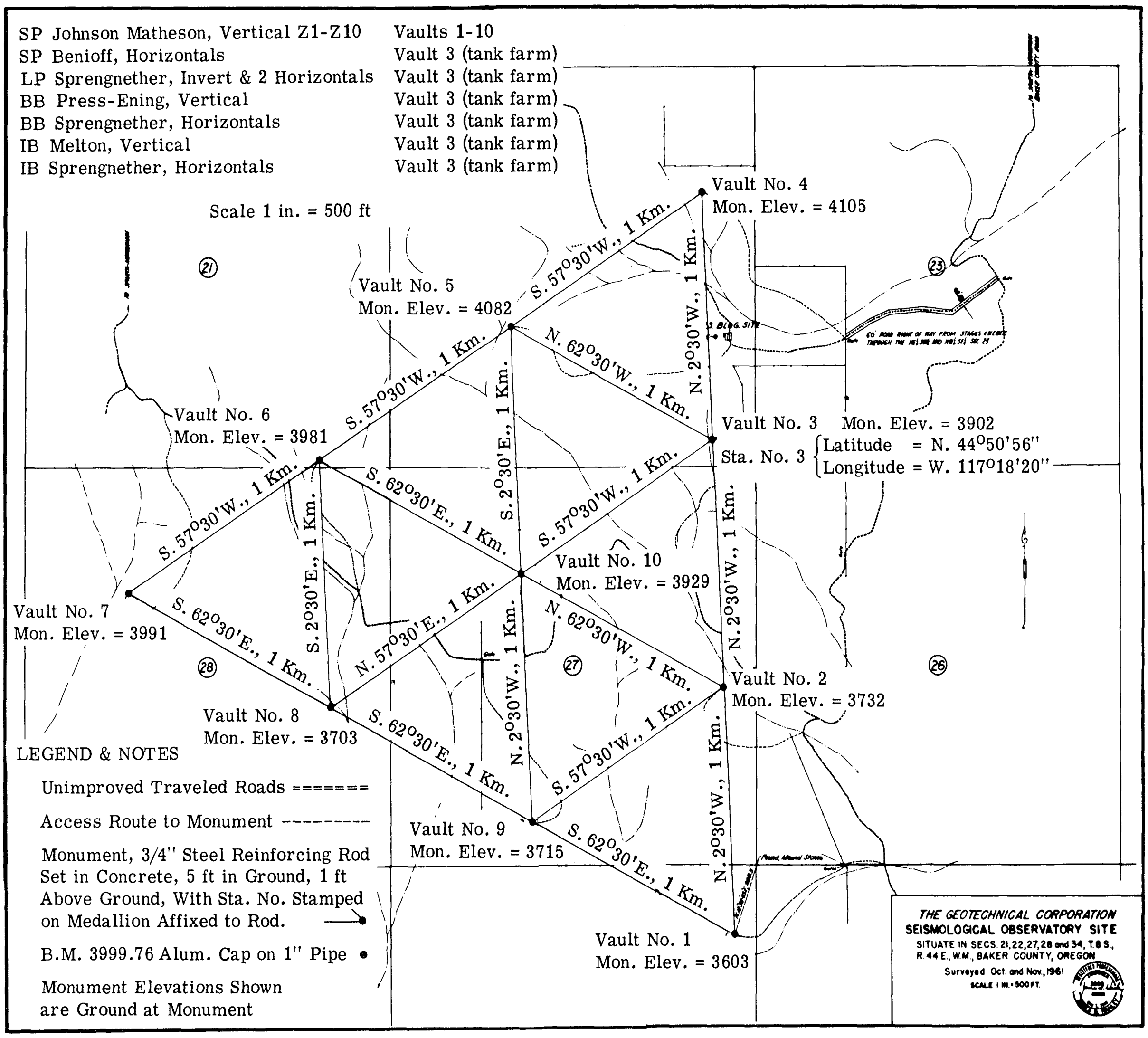

FIGURE 14. BLUE MOUNTAIN ARRAY

are buried other tank vaults, which contain 2 short-period horizontal and 3 long-period Sprengnether vertical and horizontal seismometers. Signals from the array are recorded on one Develocorder, as outlined for WMO, and those from the long-periods and broadband elements on a second line. Some recordings are also made on magnetic tape operating at 0.3 ips for spectral research purposes.

Larger arrays are now in service at the Uinta Basin Seismological Observatory, near Vernal, Utah; the Cumberland Plateau Seismological Observatory, near McMinnville, Tennessee; and the Tonto Forest Seismological Observatory, north of Payson, Arizona.

2.3.4.2.3. The Three-Dimension Array, Tryon, Oklahoma. This array, at a station 68 km northeast of Oklahoma and 1.2 km northwest of Tryon, consists of a number of deep holes spaced at selected intervals. It has the advantage of control with depth in addition to monitoring of angles of emergence. An experimental array of this sort is operated by the Century Geophysical Company under contract with the Air Force Office of Scientific Research [28]. Five abandoned oil wells 1600 meters deep, arranged in the plan of a 5-spot, are used for the array (see Figure 15). The inline spacing of adjacent wells is 402 meters. The subsurface lithology is mainly Paleozoic shales and sandstones.

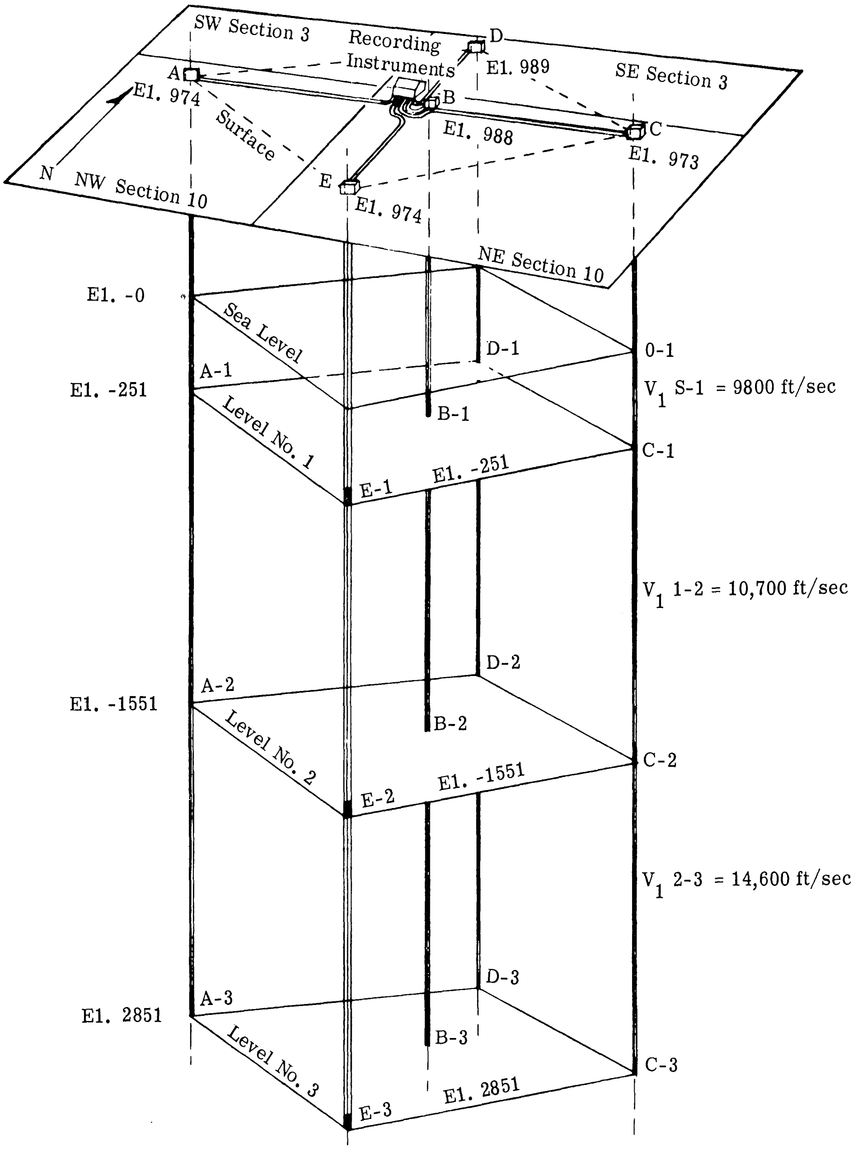

FIGURE 15. TRYON THREE-DIMENSIONAL SITE

Deep-hole seismometers were assembled by attaching preamplifiers to Hall-Sears 2-cps seismometers. These assemblies were clamped to the well casings at 3 levels: the A-level at -368 meters (considering the surface zero), the B-level at -768 meters, and the C-level at -1168 meters. Maximum drilled depth could not be used because of the difficulty of removing a plug in one of the holes. Outputs from the 15-element array, together with summation traces and a trace from a small model Benioff vertical at the surface, are recorded on a 15-channel oscillograph which operates periodically at 0.5 to 1.0 ips, and continuously on magnetic tape having a transport speed of 0.36 ips (9.1 mm/sec).

A brief summary of test results from this experiment indicates that noise from the top of the holes is not transmitted down the holes unless it is of the pulse type over an individual hole; that surface waves from local blasts definitely identified as Rayleigh waves do attenuate with depth according to theory (see Figure 16); but that culture-generated noise, e.g. from the passing of a train 1.6 km to the south, does not materially attenuate with depth (see Figure 17). Noise

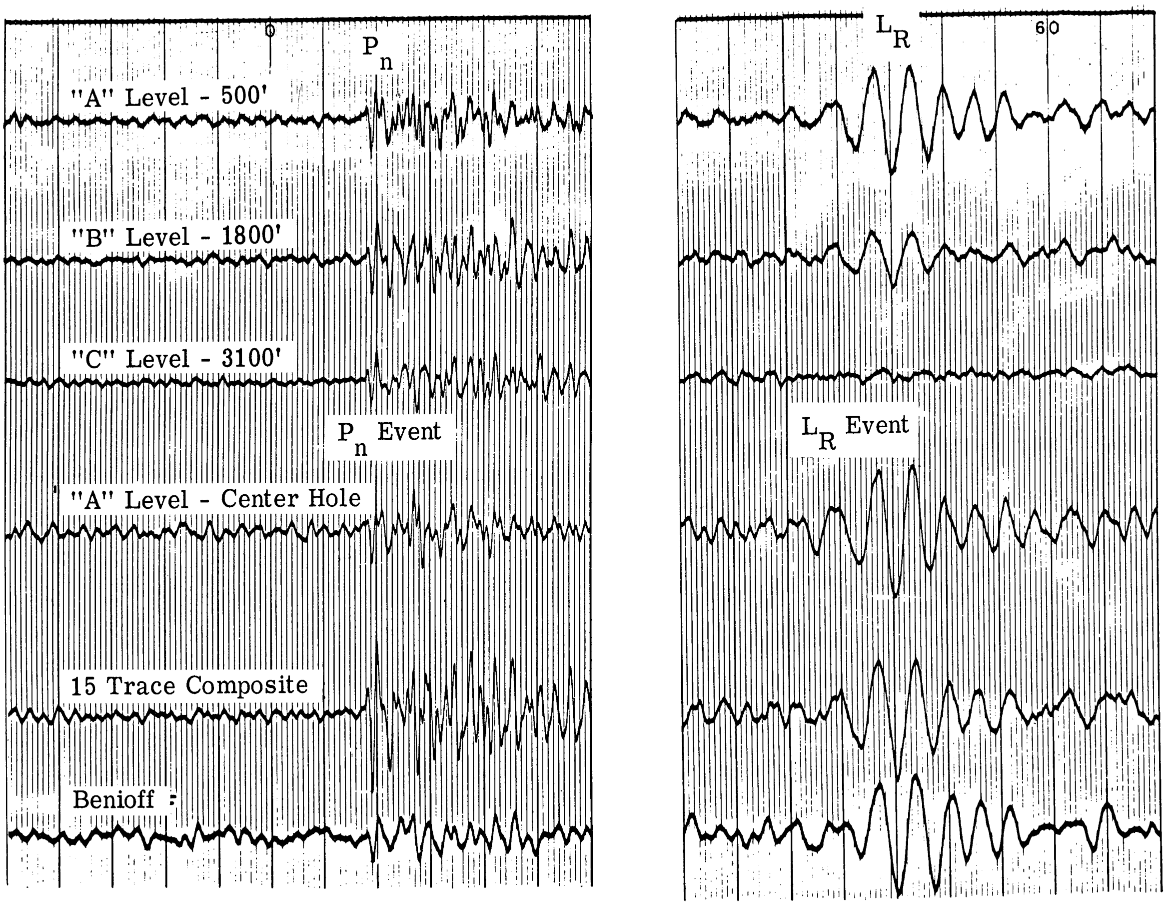

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FIGURE 16. RAYLEIGH WAVE ATTENUATION WITH DEPTH

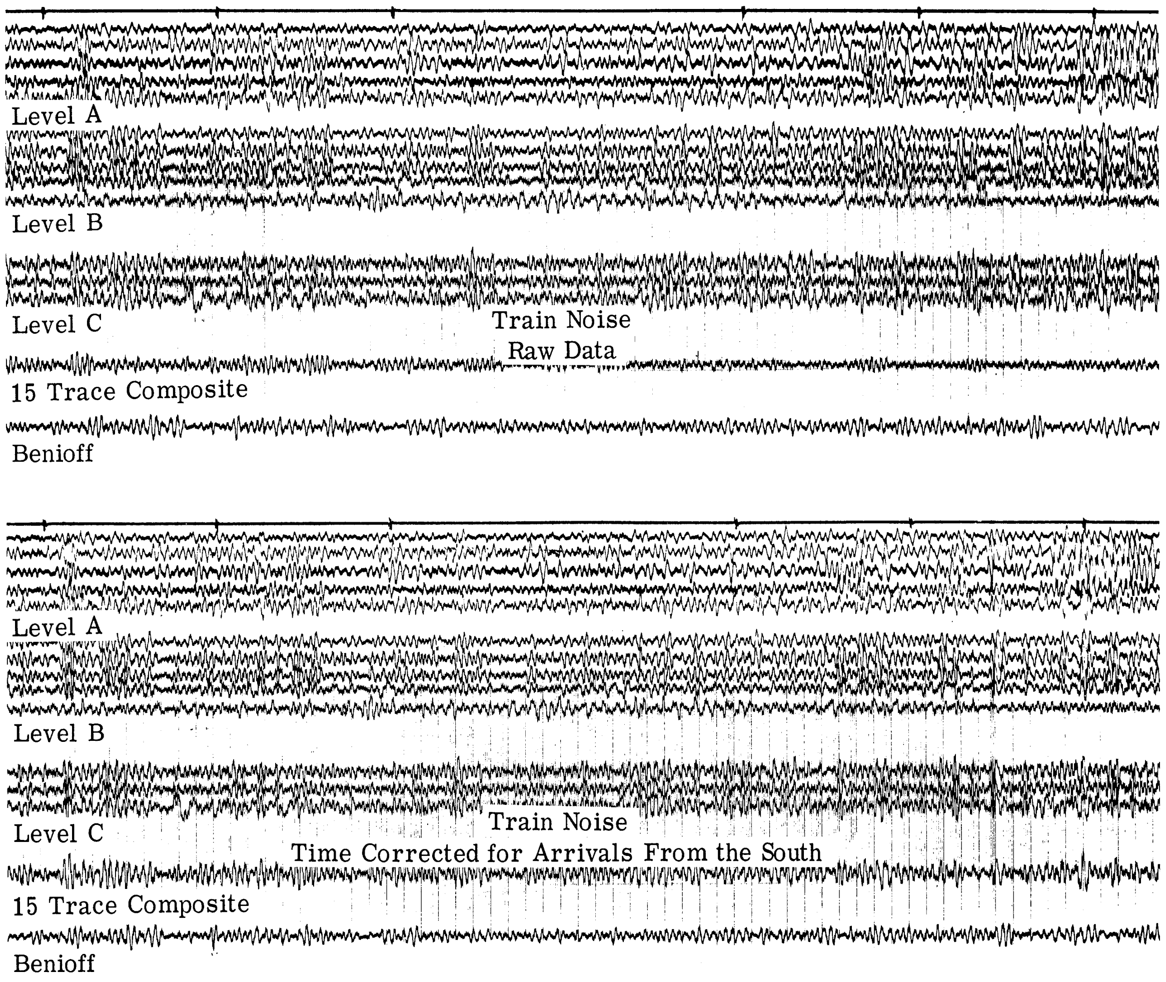

FIGURE 17. CULTURE NOISE VARIATION WITH DEPTH

in the array has frequencies from 2 to 10 cps and is apparently body-wave energy. This, in part, verifies earlier experiments, where it was observed that, in a rigid medium, preponderant cultural noise is in the form of shear, although the earlier experiments did not establish that it was in the form of body waves.

3
THE SEISMOGRAPH

A seismograph is by definition an apparatus which registers ground motion resulting from disturbances in the earth. The four parts which comprise the modern seismograph are:

1. The seismometer or detector, which picks up ground motion.

2. The recorder, which makes possible a permanent record of ground motion.
3. The communications system between the seismometer and the recorder.
4. The time reference, to a world standard, for timing receipt of seismic signals.

Items 1 to 3 are essential parts of a seismograph by definition, and item 4 is essential if the instrument is to be of value to the World-Wide network.

3.1. THE SEISMOMETER

The most commonly used seismometer consists of a dynamic mass suitably suspended, to which is attached a transducer. Modern systems are equipped to transfer mechanical energy created by differential motion between the ground and mass into electrical energy.

3.1.1. THE MOVING-COIL TYPES. The Benioff moving-coil (MC) seismometer (see Figure 18) was designed in the late 1930's and is now in limited service on four continents,

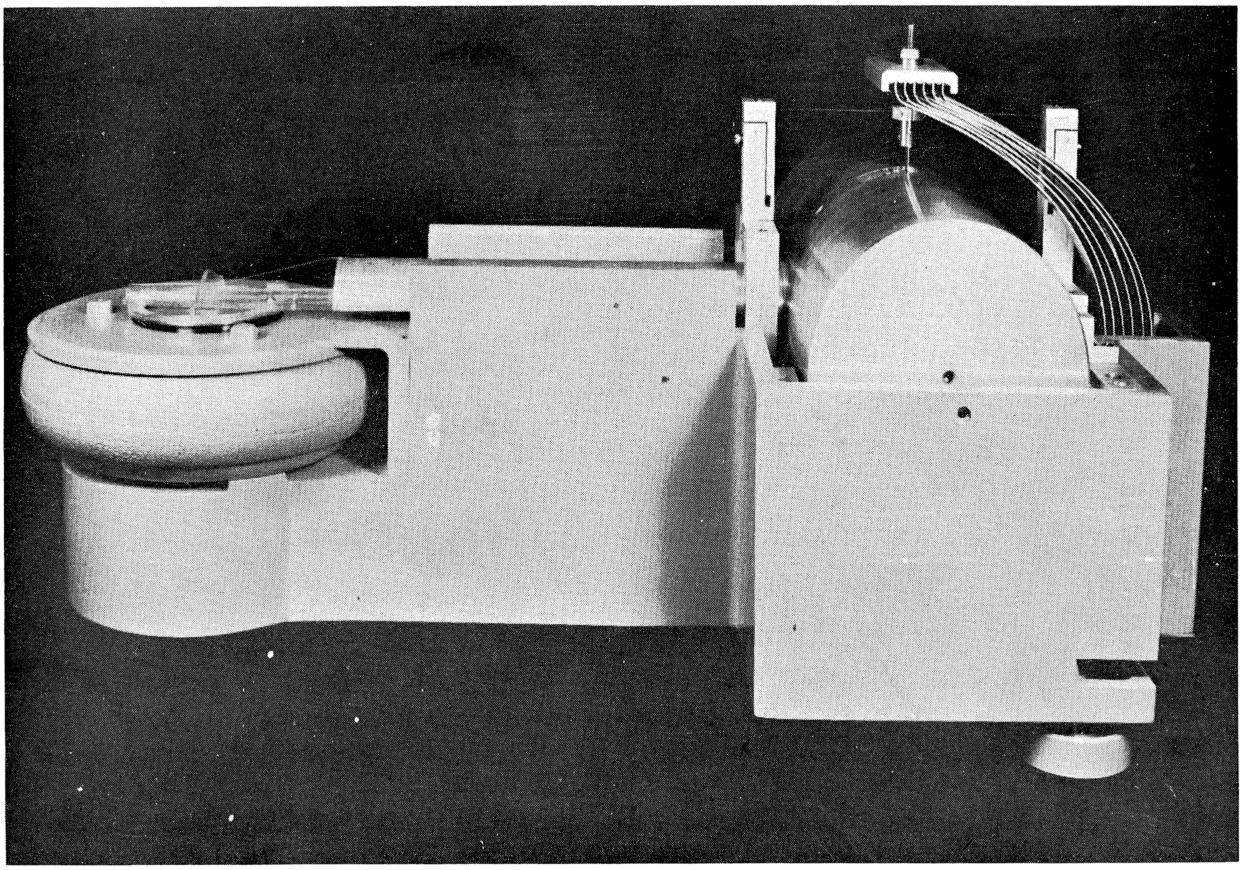

FIGURE 18. BENIOFF MOVING-COIL VERTICAL SEISMOMETER

including Antarctica. In the vertical-motion instrument, the 45-kg mass, a horizontal soft-steel cylinder, is hinged to the dust-tight supporting case and is suspended vertically by a series of arcuate springs [29]. The cylindrical transducer coil is attached to the end of a multiplying arm and is suspended vertically in a powerful magnetic field formed between the core and the outer ring of a doughnut-shaped Alnico magnet. The coil fits over the core and clears both core and ring. The horizontal-motion pickup unit is a vertical unit rotated 90^{o} so that the cylindrical mass is in a near vertical position; the arcuate springs are removed, and the case designed to fit. The free period of the seismometers is from 1.0 to 1.4 seconds. The impedance of the external circuit is such as to critically damp the system.

Most other MC seismometers are similar to the one just described except that the masses are usually lighter, and the vertical-motion units are suspended by coiled isoelastic, zero-length springs. The lesser masses of these units afford greater portability without appreciable loss of sensitivity. The Lehner-Griffith MC seismometer, for example, has a voltage output almost equal to that of the Benioff. Wilson-Lamison [30] and Sprengnether short-period seismometers are other MC seismometers available at relatively low cost. In the Melton vertical-motion seismometer the mass is suspended by a horizontal coiled spring (see Figure 19), one end of which is attached to an arm of the fixed support [31]. The period is adjustable from 0.5 to 7.0 seconds. A seismometer in general use in Russia [32] is similar to the Melton one except that the support end of the spring is adjustable vertically as well as forward and backward horizontally. Very-low-frequency 2-cps exploration-type seismometers are now coming into limited use in earthquake seismology, but electronic amplification is necessary if high gains are to be attained.

3.1.2. THE VARIABLE RELUCTANCE TYPE. The Benioff VR seismometer [33] is in wide use on every continent. The transducer system consists of coils having iron cores as a part of the pendulum mass and fixed magnets as a part of the frame [34]. The seismometer in most general use has a 100-kg cylindrical mass. The mass on the horizontal motion seismometers is suspended at each end on three steel strips placed 120^{o} apart with one strip vertical (see Figure 20). The mass is in two parts, with the transducer system in the middle. The mass of the vertical-motion unit (see Figure 21) is suspended from two oppositely wound coiled springs attached end to end and passing through the tubular center, the lower end attached to the bottom of the mass. The natural period is about 0.5 second, but the magnetic system reduces the restoring force to 1/4 that of the mechanical system, and in practice the period is 1.0 second.

The so-called "Baby Benioff," designed and constructed by the Geotechnical Corporation, is in limited use. The transducer system virtually constitutes the dynamic mass.

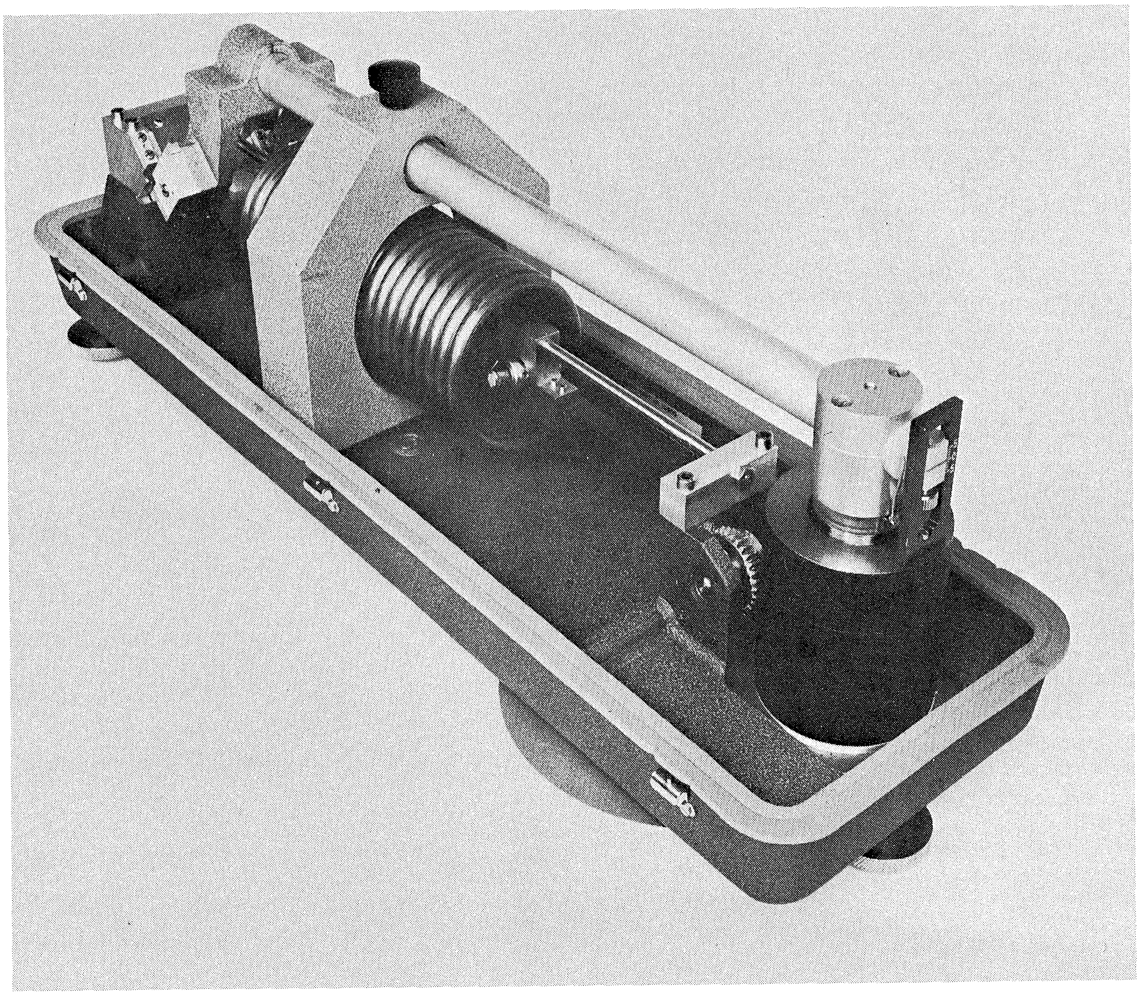

FIGURE 19. MELTON VERTICAL-MOTION SEISMOMETER

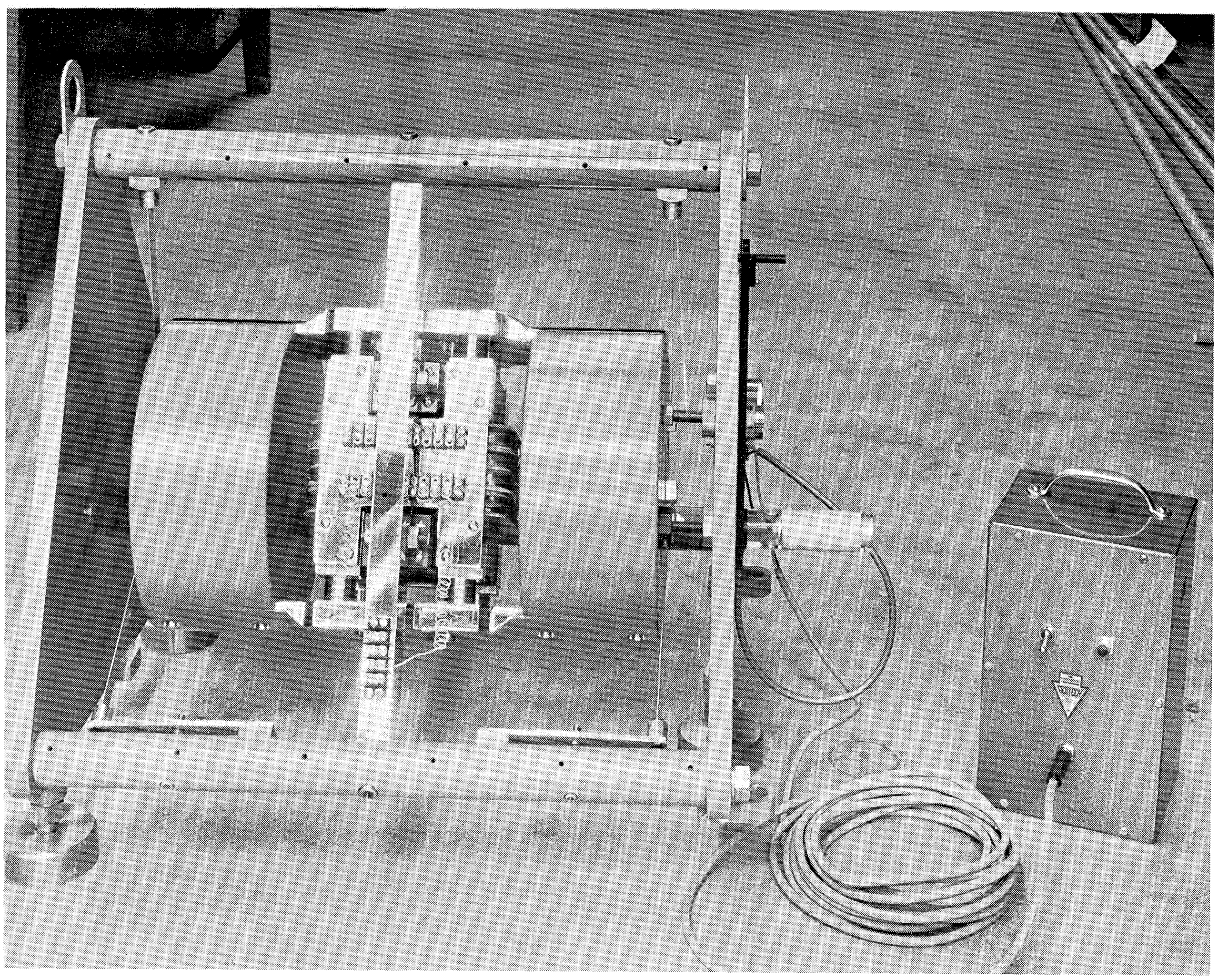

FIGURE 20. BENIOFF VARIABLE-RELUCTANCE HORIZONTAL SEISMOMETER

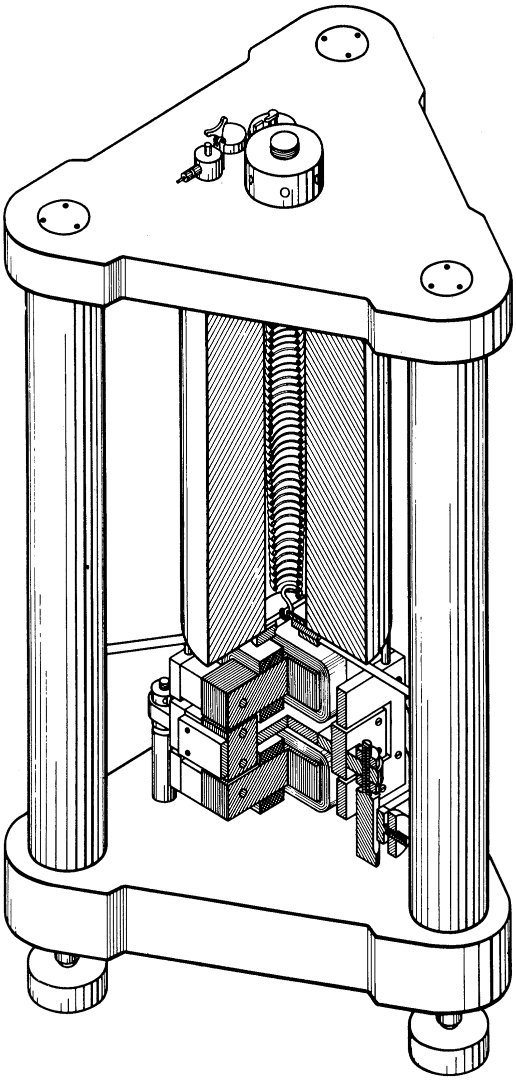

FIGURE 21. BENIOFF VARIABLE-RELUCTANCE VERTICAL SEISMOMETER. The spring system in late models consists of two oppositely wound springs placed end to end and attached near the center of the mass.

3.1.3. MOVING MAGNET SEISMOMETERS. In this type, the transducer coil is attached to the support and the magnet is a part of the dynamic mass. The two Willmore seismometers, designed by P. Willmore and manufactured by Hilgar and Watts, are in widespread service, especially in the British Commonwealth. Both are relatively small and inexpensive. Both have an advantage over models described heretofore in that with a simple internal change they can be operated as either horizontal or vertical instruments. Both are equipped with watertight cases and can be buried without protection, thus eliminating seismometer vault expense. The Mark I has a period of 1 cps; the period of the Mark II can be adjusted from 1/3 second to 3 seconds, which makes it a versatile research instrument. Both are available with either low-impedance coils, for use with galvanometers, or high-impedance coils, for use with amplifiers. The Mark I has given excellent service in detecting P waves.

The Johnson-Matheson seismometer (see Figure 22), designed in the laboratory of the National Bureau of Standards [31], is currently being used in array seismology. It is somewhat

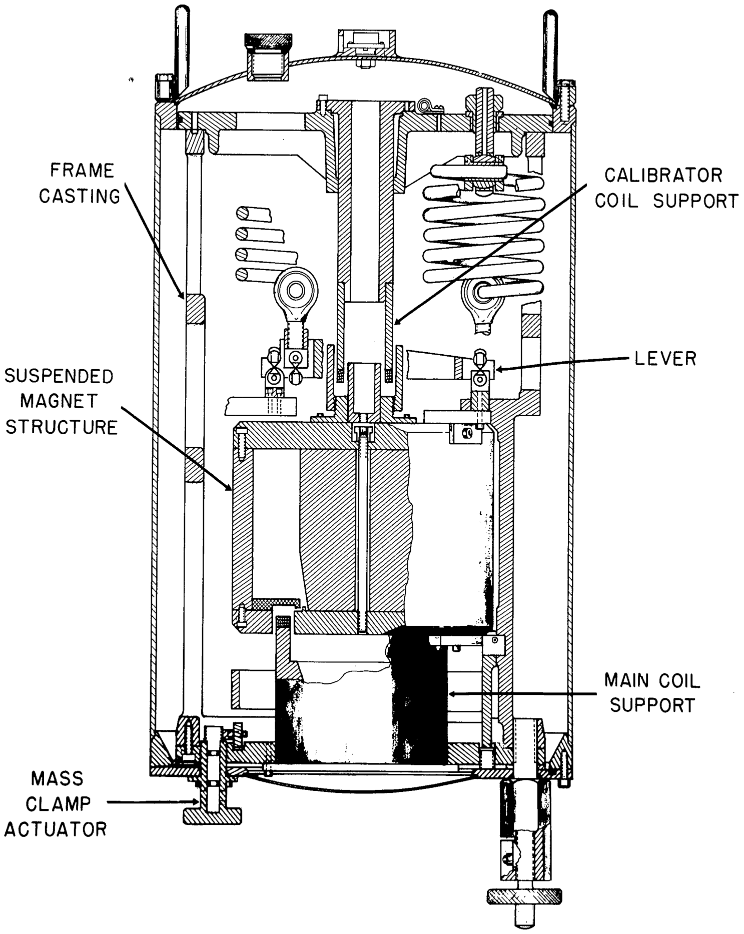

FIGURE 22. JOHNSON-MATHESON VERTICAL SEISMOMETER

larger than the Willmore, and its period is 1.25 seconds. With a watertight case, it can be operated under several meters of water.

If the borehole is large enough, a 1-cps borehole seismometer recently designed and constructed by the National Geophysical Corporation has considerable promise. As of this writing, results of field tests are not available.

3.1.4. THE BOREHOLE SEISMOMETER. In an effort to reduce the effects of background noise by going deep underground, VELA UNIFORM requirements brought forth the borehole seismometer. High-frequency assemblies have been in general use in exploration for several decades. However, requirements for a 1-cps unit have made the problem somewhat more difficult.

The apparatus must function in a hole 10,000 feet deep at temperatures to 150°C, where corrosion may be great and where the hole may be inclined by as much as 10°. Provisions for recalibration and recentering must be made, and the response must be equal to that of surface instruments.

One down-hole seismometer is equipped with moving coil transducers. To obtain proper damping, large magnets were required which, for a 100-kg mass, necessitated constructing the mass in several sections with a transducer for each section. A second seismometer (Figure 23) has a VR transducer which functions with smaller magnets so that only one mass is required.

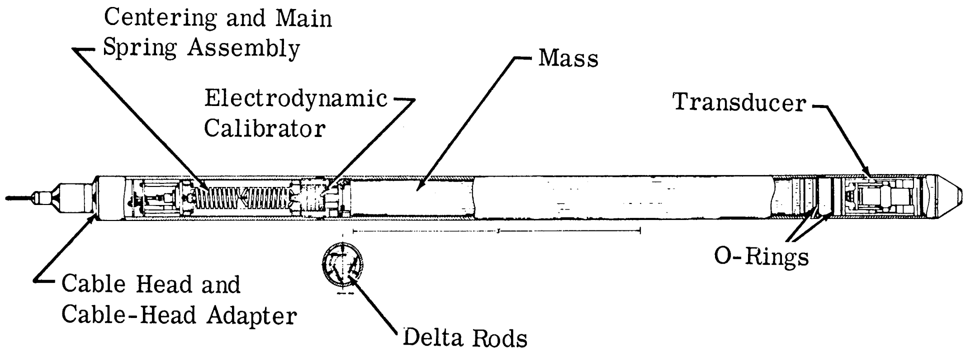

FIGURE 23. DEEP-WELL SEISMOMETER, MODEL 11167, VARIABLE-RELUCTANCE TYPE

3.1.5. VERTICAL SEISMOMETER SUSPENSION SYSTEMS

3.1.5.1. Spring-Mounted Systems. Heretofore, the dynamic mass of a vertical-motion seismometer has been held in place by a spring or a series of springs. To avoid the effects of temperature changes, and elastic hysteresis, and other troubles, considerable care in the design and selection of the spring is necessary. In addition, unless the spring is properly designed, the seismometer is subject to a troublesome second-order effect which results in a complicated response to ground motion. Now we have the zero-length spring, in which the length of the spring is proportional to the load; and a temperature-compensated spring, made up of two metals which have different coefficients of expansion and are constructed so that effects from temperature changes are compensated. Until lately a fairly uniform temperature in the seismometer vault was necessary; but the recently developed temperature-compensated systems gives greater temperature tolerance.

3.1.5.2. A Magnetic Suspension System. A novelty consisting of a bar magnet suspended with no apparent support except that it is guided by an upright frame has been available for some time. Suspension, of course, is achieved by magnetic repulsion. The idea was not applied to a seismometer system until recently. The so-called "Springless Sprengnether," a design of the Sprengnether Instrument Company, is probably the first seismometer to which this principle was applied. This design uses magnetic attraction, not repulsion. Figure 24 shows a schematic diagram of this instrument. R and Q are two ring-shaped multipolar magnets, with the poles facing each other as shown. R is a part of the dynamic system, free to rotate about its axis, which is normal to the plane of the paper. Q is rigidly attached to the frame, except that it can be rotated manually in the direction of the arcuate arrow. The mass M and its boom make up the rest of the dynamic system. The forked section of the boom straddles Q and is rigidly attached to the two sides of R. The dynamic system is supported by two sets of crossed Cardan hinges placed along the axis of R. To bring the system into suspension Q is rotated (counter-clockwise in the diagram) until the magnetic attraction between the poles exactly balances the gravity moment of the dynamic system.

At the time of writing, this instrument is in the prototype stage. It has been satisfactorily proved in trial runs along with other high-sensitivity seismographs. Tests through great ranges of temperature remain. Theoretically temperature changes within operational limits should not require vertical adjustments; this is the instrument's great potential advantage. Its limitation is that the mass moment cannot exceed the magnetic attraction. Seismometer periods of about 1 second have been reached.

Other springless vertical seismometers have been considered. In one the mass rests on a stack of piezoelectric plates, and in another the detector is a deep-hole vertical strain seismometer responsive to short periods. These systems have not yet been used in earthquake seismology.

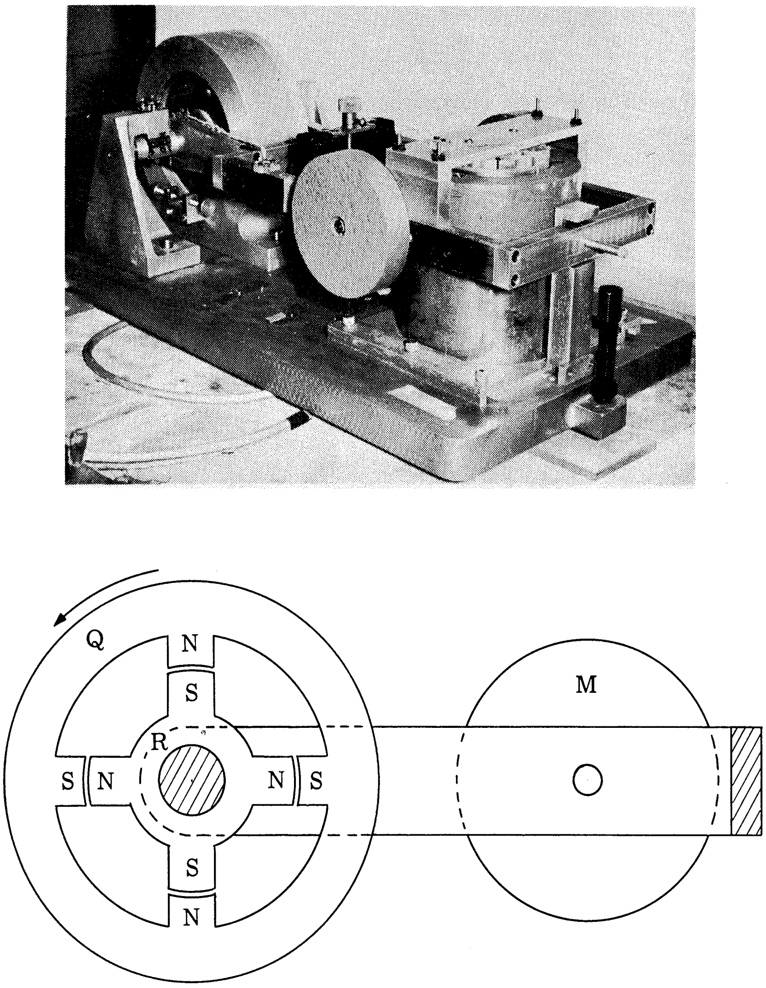

FIGURE 24. SPRENGNETHER MAGNETICALLY SUSPENDED VERTICAL SEISMOMETER

3.2. THE SEISMOGRAPH RECORDER

3.2.1. THE TRANSLATING DRUM TYPE. This recorder consists of a rotating drum containing a sheet of record paper or film which translates as it rotates so that an entire span of unattended operation, usually 24 hours, is contained on a single sheet. For recording short-period waves, the peripheral speed of the drum is 60 mm/min on paper, or 15 mm/min on film. The effective length of the record is 90 cm, with about 2 cm for overlap. If paper is used, the sheet is 30 cm wide; if film 35 mm. Three-component operation requires three drums, which may or may not be on the same shaft. Film recorders in common use have four film channels, two drums of two channels each or four drums of one channel each, operating on a common shaft. The fourth channel, if used, records automatic time signals to calibrate the local chronometer.

Film recorders using 70-mm wide strips, designed for 72 hours of unattended operation, are in service in a number of relatively inaccessible stations in southeastern Australia. The "stylus" on recorders using film or photosensitive paper is a sharply focused point of light reflected from a galvanometer mirror. Focus is super-sharp on the film recorders, because the record must be enlarged eight to ten times without losing definition. Other record sizes and drum speeds are in use, but the ones mentioned are the most general. Ink and heat styluses, described later, and delicate mechanical styluses writing on smoked paper, are widely used for visual recording.

3.2.2. THE MOVING-TAPE TYPE. In this case a considerable number of traces from different detectors are recorded side by side. Most exploration seismographs record on rapidly moving photo-sensitive paper or magnetic tape, and operate for a few seconds only. If recording is continuous, the tape speed must be slow for economic operation. Several ink-recording seismographs using paper tape were in operation a few years ago, but they have become obsolescent because of the uncertainty of ink recording and because of storage and processing difficulties. However, two types of moving tape recorders have great potential usefulness.

(a) The Develocorder, developed by the Geotechnical Corporation, permits recording of 20 traces side by side on continuously moving 16-mm film. The sensitive side of the film is automatically developed, fixed, and washed very soon after exposure, and within eleven or twelve minutes is available for viewing on a ground glass screen which is a part of the recorder. This permits side by side viewing of traces from an array or from a multi-unit telemeter system without loss of time.

(b) Magnetic tape recording is probably the most versatile, but is relatively expensive in first cost, operation, and storage. The best systems record a frequency modulated carrier wave. Recording resolution is improving with increasing technical know-how. As of 1963, frequencies from DC to 50 cps can be resolved on tape moving at 0.3 ips which uses a 10.5-inch roll in 24 hours of operation. Other resolvable maximum frequencies are in proportion to the tape speed.

Magnetic tape offers the advantages that it can be played back at any desired speed, and desirable signals can be transferred to another tape, the originals erased, and the tape reused. A desired record may be transferred to a loop and subjected to detailed frequency and other analyses, and it can be reproduced as a visual record which is almost identical to a simultaneous record from direct recording.

3.2.3. HOT WIRE RECORDING. The Helicorder, produced by the Geotechnical Corporation, is in wide use. The stylus is the end of a hot resistance loop gliding on the surface of heat-sensitive paper wrapped about a standard drum. The traces are sharp and resolution high. Performance is somewhat superior to ink recording and almost equal to photographic recording. Cost of operation is about the same as the latter. However, the records are easily mutilated, and are subject to deterioration with hard use or storage.

3.2.4. LONG DURATION RECORDING. The Autocorder, a 60-day recorder, was developed by the Sprengnether Instrument Company. Outwardly, it has nearly the same appearance as a standard drum recorder. It will produce 24 hours of record at 60 mm/min, as does a standard short-period seismograph recorder. At the end of a recording period, recording ceases; the drum returns to the starting position; the exposed paper is conveyed to the interior of the drum; a new supply is drawn into place from a roll of unused paper, also on the interior; and a new recording day starts. The changeover process requires about one minute, and loss of record because of the width of the silt through which the paper is drawn does not exceed 1 mm. Duration of unattended service is in inverse ratio to the paper speed. A 200-foot roll will give 60 days of unattended operation at 60 mm/min. Processing a 200-foot roll of unmarked photographic paper without confusing the dates and/or losing accurate time control is another matter.

Magnetic tape recorders operating at 0.02 ips will store 30 days of record having frequencies of 5 cps or less on one 14-inch roll of tape.

3.2.5. DRIVING MECHANISMS. Uniformity of recorder operation is highly important. Mechanical drives governed by a conical pendulum with weights providing the motivation power are being used in Europe and elsewhere. Synchronous motors are in most common usage. They have the disadvantage that their speed varies with the frequency, which is somewhat erratic in isolated areas provided with diesel electric power. Electronic drives of more recent adoption are the most reliable. These drives may be a part of the time standard mechanism.

3.3. SEISMOMETER-TO-RECORDER COMMUNICATIONS SYSTEM

In direct recording mechanical seismographs, motion is communicated to the recording drum by a mechanical lever ending in a stylus. In a photomechanical system it is communicated by an optical lever ending in a sharply focused beam of light. In electromagnetic types, motion is communicated through an electrical connection of resistance networks to the galvanometer. Electronic systems are various: a direct or indirect feed to an amplifier at one end, and to galvanometers or record heads at the other; filters, modulators, demodulators, etc. are included in the circuit as necessary.

3.4. TIMING SYSTEMS

An automatic seismograph time marker has two parts: the chronometer with its programmer, and the time-marking radio for calibrating the chronometer.

The chronometer may be an accurately adjusted pendulum clock with a built-in programmer; it may be a marine chronometer, manually or electrically wound, and equipped with minute or half-minute marking contacts, and an external programmer; or it may be an electronic chronometer. Electronic clocks are frequency regulated by a tuning fork in a temperature-regulated oven; or by a crystal in a temperature-regulated oven together with frequency dividers which terminate in the frequency of a synchronous motor driving the clock. Electronic clocks have the advantage that they are highly accurate, 5 parts or less in 10^7, and they can frequency control the driving mechanism of the recorder. They have the disadvantage that they are initially expensive, and their operation is relatively complicated. The last is not really a disadvantage. Just as repair of an electronic clock requires an electronic expert, repair of a mechanical clock generally requires a chronometer expert; and chronometer experts are scarcer.

The chronometer programs displacements of the trace at fixed time intervals, usually once each minute, and an additional mark, or no mark at all, once each hour. Other intervals are used, 1 each 30 seconds or 1 each 10 seconds, with no mark at the minute. For efficient operation, film recorders require additional programming. On Geotechnical film recorders, time marks are programmed once each 10 seconds with no mark at the minute, and longer marks at other programmed intervals. These interval marks are recognized, if the background permits, by relatively long displacements of the trace. Early in the 1940's, the Coast and Geodetic Survey [29] adopted a method of marking by brightening the source lamp for a second or two at programmed intervals; this results in an easily recognized darkened trace. The adopted intervals follow a definite code which permits fixing the accurate time of a signal seen on the screen of a viewer within a few seconds after it is observed. This system is believed superior to others, although there is a risk of shortened life of the source lamps.

For accurate time control, radio marks from a time broadcasting system should be automatically placed on the record at least four times daily if the chronometer is mechanical, or at least once each day if it is electronic. In fact, on some electronic clocks, the chronometer output can be synchronized with WWV or other broadcast signals.

4
THE SEISMOGRAPH STATION

This section, partly a summary of earlier sections, discusses the selection of station sites, the problem of background noise and how to reduce it or minimize its effects, and instruments in general use today. Earlier papers [1, 36] emphasized the importance of adequate seismographic coverage, with emphasis on operation by universities. This emphasis is being retained here except for a few specialized cases beyond the facilities of most universities. These will be discussed first.

For any seismograph station, the selection of instruments depends of course on available facilities in relation to background noise and available funds. A highly sensitive short-period seismograph cannot be operated efficiently in a locality subject to high background noise. However, if the high background is only intermittent, resulting from traffic during the day or heavy surf during winter months or stormy periods, the highly sensitive equipment can be used for recording during the quiet periods, and equipment more suitable to the area can be used during noisy periods.

In the following discussion, classes A to C refer to stations equipped with electromechanical seismographs which record short-period seismic waves. Class A stations are considered optimum and will be discussed first. In the discussion T_0 is the seismometer period and T_g the galvanometer period. The galvanometer is normally driven by earth power through a resistance and voltage divider control, and recording is photographic. However, electronic amplification is needed for driving ink or hot-wire recorders, for telemeter systems, and for actuating recording heads of magnetic tape recorders.

4.1. CLASS A STATIONS

Stations in this class have peak sensitivity in the period range 0.05 to 1.5 seconds. Effective peak magnification for a 1-second wave is 200,000 or more.

4.1.1. A-1—THE ARRAY STATION. There are intermountain areas where background noise in the 1-cps range is 2 $m\mu$ or less. The Blue Mountain Observatory in northeastern Oregon is an example. The array suggested here is more elaborate than that at Blue Mountain, and should be little more expensive.

The array suggested by L. F. Bailey for an A-1 station is illustrated in Figure 25. It is a series of 19-element arrays arranged in the form of concentric hexagons stepped down by octaves. Each array of the series is illustrated in the insert. It consists of 12 elements on the periphery,

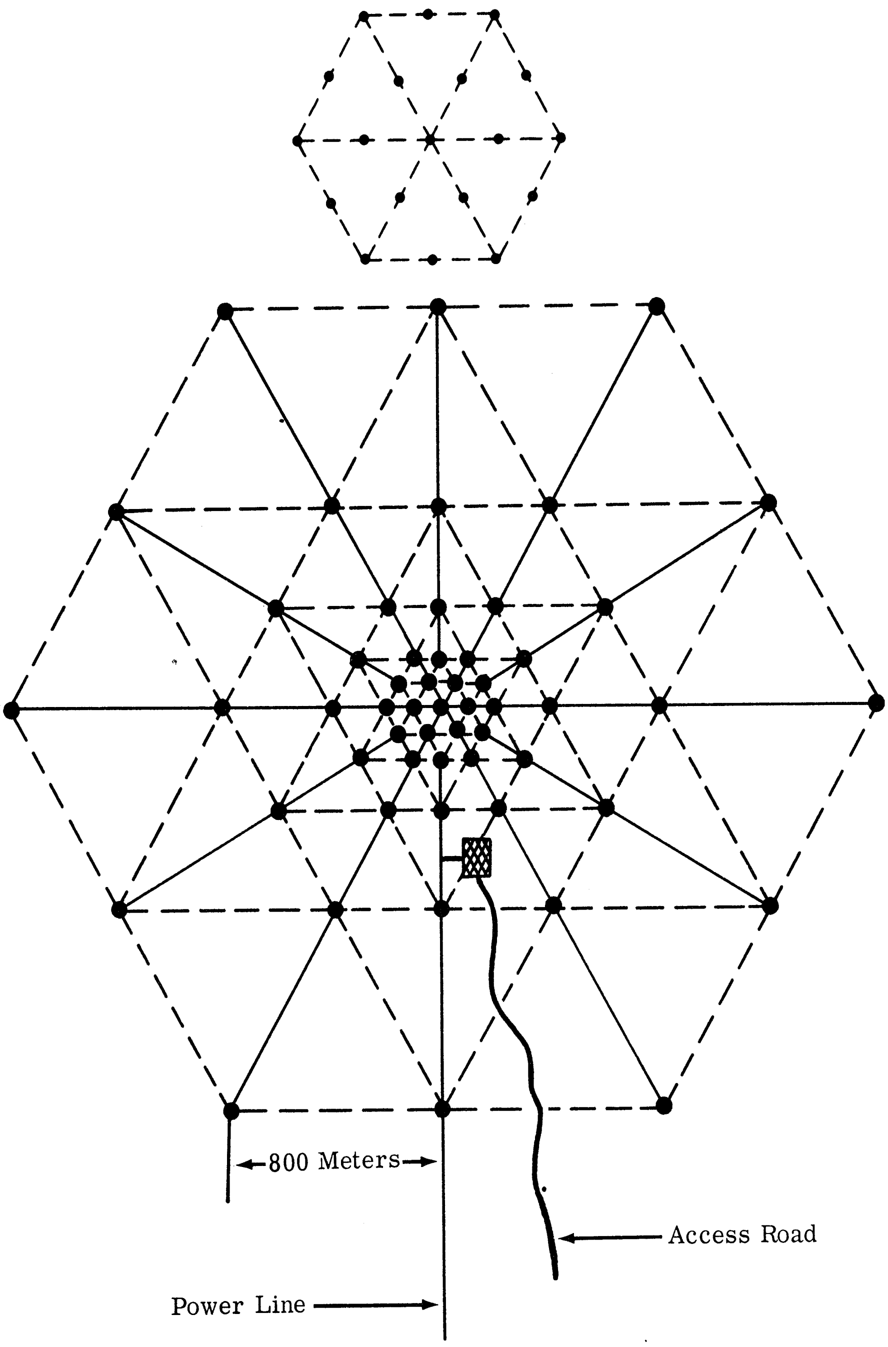

FIGURE 25. SUGGESTED SEISMOMETER ARRAY FOR AN A-1 STATION

six elements at mid distance to the center, and one element at the center. The larger illustration shows four such arrays nesting downwards so that each smaller array has half the diameter of the next larger one. The dimensions of the array depend on the wave speeds of local background noise. Under average conditions, suggested dimensions are: for the diameters of the outer and consecutively smaller inside arrays, 3.2 km, 1.6 km, 0.8 km, and 0.4 km; and for the separation of the elements in the respective arrays, 800 meters, 400 meters, 200 meters, and 100 meters. This makes a total of 55 elements, since many of the elements are common to two or more of the arrays. This permits wavelength filtering in four octaves. In theory, it will selectively reject noise (Rayleigh or SV waves) having average velocities in the 1- to 10-cps band. In practice, much depends on the spacing, on the nature of the subsurface media, and on the ability to provide duplicate instrumental characteristics including uniform gain settings. Selective weighting or increase in gain settings of the elements toward the center should increase the efficiency of the array.

Each element should consist of a 1-cps small-model vertical seismometer buried several feet deep, preferably in a small canister. Johnson-Matheson, National 1-cps, Willmore, or similar seismometers of other makes are suggested. Sprengnether's springless model, if proved, should not need to be buried more than about a foot deep. Preamplifying signals at each seismometer station should obviate the necessity for expensive wire connecting the elements with the central recording facility; this would offset some of the cost of preamplifiers. If funds permit, a class A-1 station should include an array of three or four deep-hole stations for the purpose of determining the emergence angles of incoming signals.

The class A-1 station suggested here includes an array of seismometers arranged in a pattern believed to be the optimum consistent with reasonable available funds. It also includes other seismometers, and the necessary recording facilities. This means not that a recording channel should be provided for the output of each element in the array, but that, by appropriate selectivity and weighting, selected elements and combinations of elements can be recorded. Magnetic tape recording is recommended for this purpose. Instrumentation should therefore include:

Seismometers:

Array seismometers (with preamplifiers); one set of three-component short-period; one set of three-component long-period.

Deep-hole seismometers in an array if possible, for experimental comparative recording.

Recorders:

Conventional film or paper recorders, one drum for each seismometer not of the array.

Develocorders, rate not exceeding 15 mm/min, preferably two for recording from the array.

Magnetic tape recorders, rate 0.3 or 0.6 ips, with at least 19 channels for recording from the array and three more channels from the high-frequency seismometers.

Magnetic tape recorder, 0.02 ips, for experimental long-range recording from long-period and short-period seismometers.

Two or three Helicorders for sampling from the array and/or individual seismometers.

One ink recorder for continuous visual operation.

One 12-channel visicorder for reproducing direct or filtered signals from the magnetic tapes.

Communications

The array: Preamplification at each unit will materially reduce the cost of wire leading from elements of the array. This reduction can be accomplished by radiating power lines outward from the center, and, where practicable, by returning the seismometer outputs over the same facility. Preamplifiers in common use are virtually the first stage of a telemetering system.

The galvanometer and galvanometer bridge. Lehner-Griffith or Geotech galvanometers are recommended. Manufacturers of short-period seismographs usually supply 5-cps galvanometers. If the seismometer has a period of 1.0 second, the seismometer-galvanometer connection in general use has a peak magnification for periods of about 0.3 second (see Figure 26). This combination seems to give the best results on oceanic islands and perhaps in certain coastal areas where 1-second microseisms are prevalent over shorter-period ones, especially if the station site is fairly free from culture noise.

If the galvanometer has a period of 0.5 second (2 cps), the seismograph is less sensitive to culture noise or to disturbances caused by wind blowing on nearby rocks, trees, or buildings. In a conventional seismograph station, a 0.5- to 1.0-second galvanometer is recommended. For arrays, oceanic islands, and certain coastal areas, 0.2-second galvanometers are recommended.

The seismometer-to-galvanometer coupling circuit is shown in Figure 27. Gain is adjusted by varying the shunt resistances; the series resistances must then be adjusted if the damping balance is to be maintained. Circuits provided by the Geotechnical Corporation do this automatically.

Timing. A crystal-controlled electronic chronometer (time or frequency standard) is recommended. This standard should control the frequency of all recorder drives. Frequency standards supplied by some manufacturers have a built-in radio for calibrating with a world time standard.

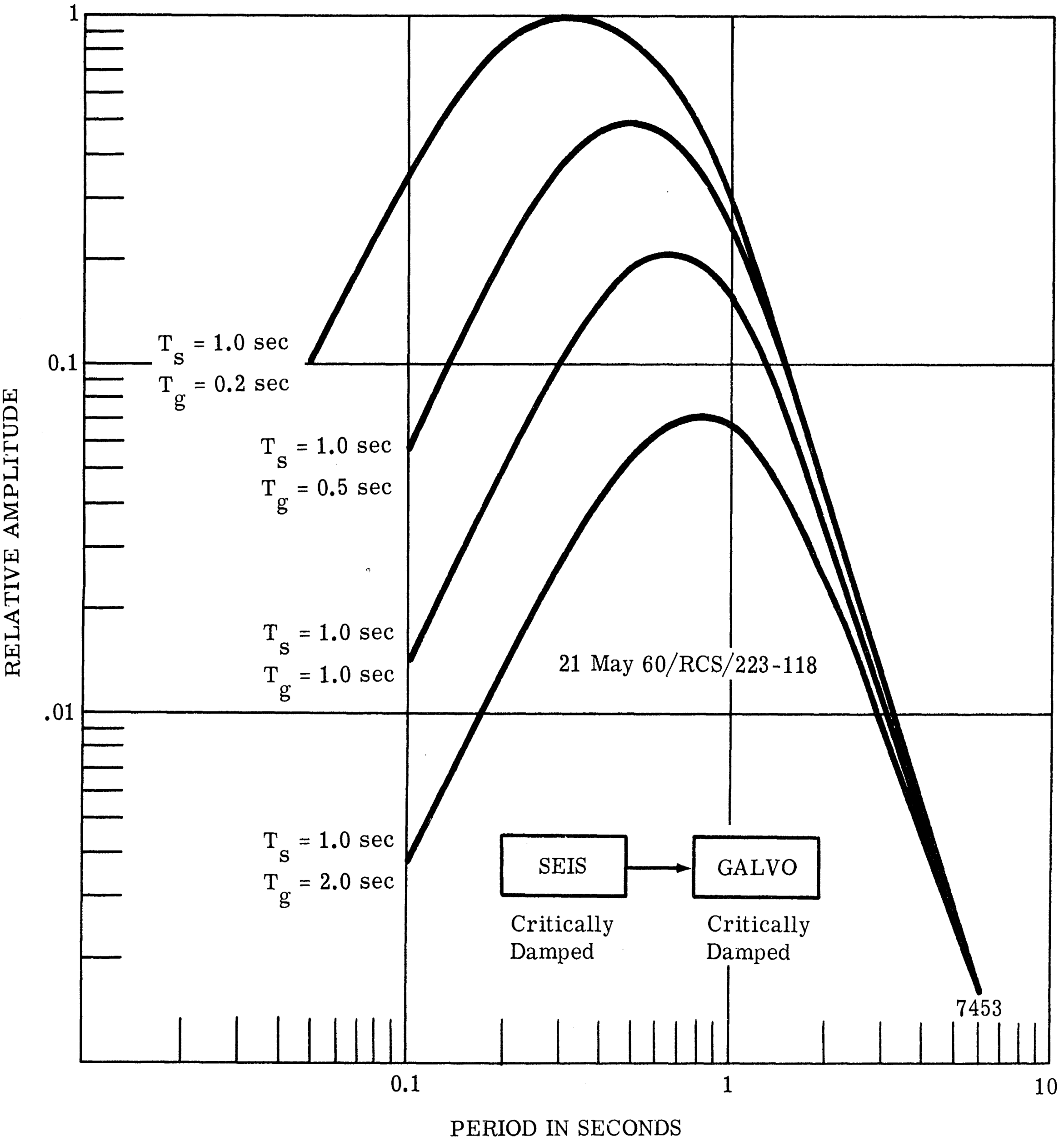

FIGURE 26. AMPLITUDE RESPONSE CURVES OF VARIABLE-RELUCTANCE SHORT-PERIOD SEISMOGRAPH USING GALVANOMETERS WITH PERIODS OF 0.2, 0.5, 1.0 AND 2.0 SECONDS

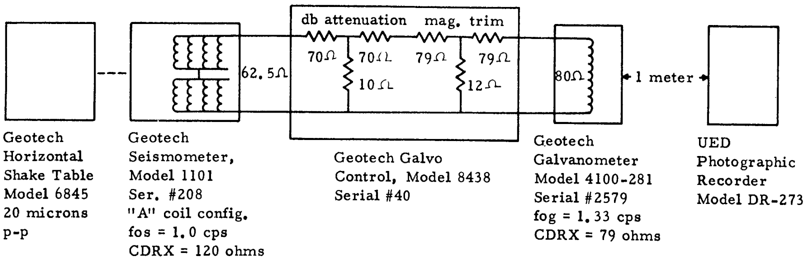

FIGURE 27. GEOTECH ATTENUATION UNIT

Seismometer vaults. Housing for the array seismometers has been described: a buried watertight canister just large enough to hold the seismometer and preamplifier. See Class A-2 for other seismometer housing.

Office and recorder housing. The Blue Mountain Station (see Figure 28) serves as an example of housing requirements of an array station. The outbuilding is for storage of supplies and equipment. The main building is provided with (1) a dark room with galvanometer and recorder piers; (2) a photographic dark room for processing photo paper; (3) a room provided with various visual recorders; (4) an instrument panel for control of circuits from the array, which includes a magnetic tape recorder (two or more are needed for the array proposed here); (5) office space; (6) a wash room; and (7) temperature control apparatus.

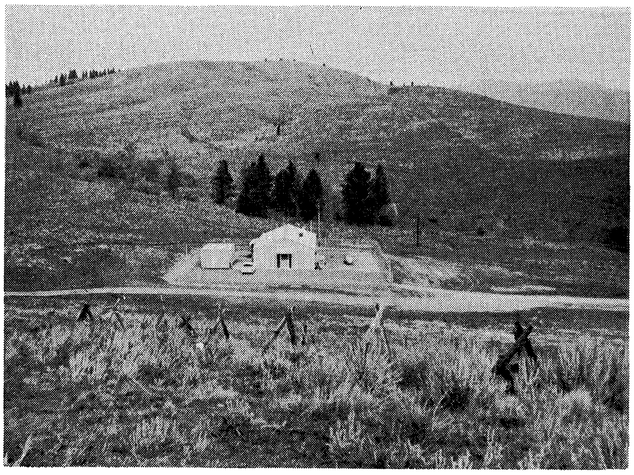

FIGURE 28. BLUE MOUNTAIN SEISMOLOGICAL OBSERVATORY

4.1.2. CLASS A-2 STATIONS. These are first class, non-array stations. A Coast and Geodetic Survey World-Wide Standard seismograph station, which adequately represents a station in this category, has the following facilities:

Seismometers. Benioff (Geotech) short-period VR-3 components; $T_0 = 1.0$ second, $T_g = 0.75$ second; external critical damping resistance, 80 ohms; galvanometer sensitivity, 10^{-9} amperes per mm trace deflection at 1 meter.

Sprengnether long-period, three-component; $T_0 = 30$ seconds, $T_g = 100$ seconds.

Recorders. Photosensitive paper on 30- × 90-cm drums, one drum for each galvanometer; paper speeds 60 mm/min for short-periods and 30 mm/min or 15 mm/min for long-periods.

Time and Frequency Standard. Crystal controlled with built-in radio programmed to receive time signals at 6-hour intervals.

Power supply. 28-volt Nickel-Cadmium (Nicad) batteries, with trickle charger. Driving motors are frequency controlled by the time standard.

Housing. Figure 29 is a housing plan recommended for a world standard seismograph. For better operation, the seismometer vault should be isolated 100 meters more or less from the recorder building, and on competent bedrock if at all possible. The long-period instrument should be temperature protected with styrofoam covers whose tops are provided with anti-convection heat control.

Discussion: Specification for a World-Wide Standard seismograph, outside of housing, background level, and underground conditions, are unvarying. Otherwise the seismograph would not be standard. The only variable is the gain, which must be adjusted according to the background noise level.

Recommended instrumentation for non-standard Class A-2 stations includes:

Seismometers.

Three-component sets of either Benioff MC or VR; Lehner-Griffith MC; Johnson-Matheson; Willmore; or National 1-cps.

One "Springless Sprengnether" vertical

Three long-period seismometers with photo paper recorder and 90- to 100-second galvanometers.

Recorders.

Paper recorders as for standard stations.

Film recorders for SP seismographs.

Develocorder if telemetering from other stations is employed.

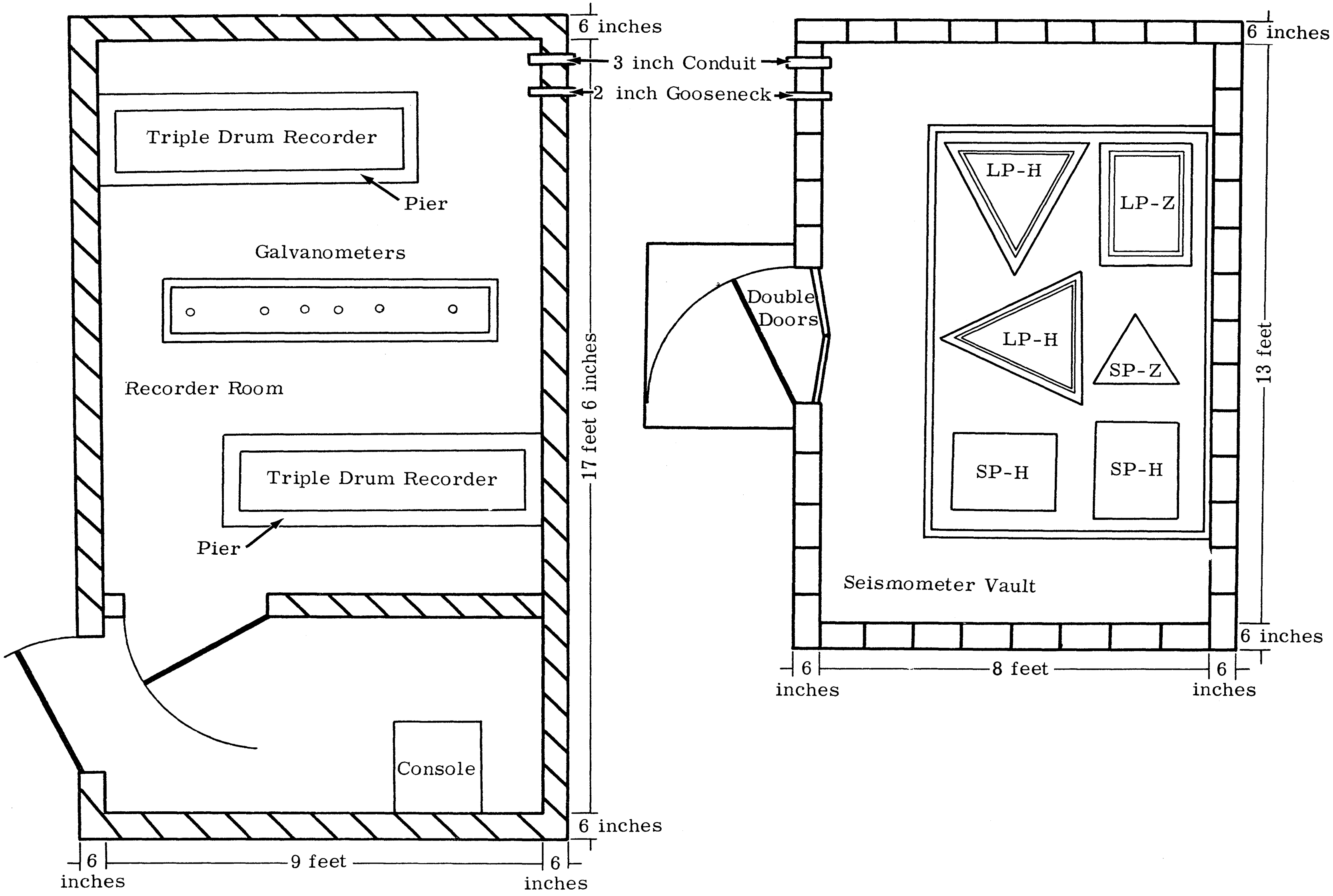

FIGURE 29. MINIMUM STATION FACILITY FOR WORLD-WIDE SEISMIC INSTRUMENTS

Advantages of paper and film recording:

Paper — The entire record can be scanned quickly and read with greater speed. Reading requires no projector or enlarging apparatus, and results in less eye strain.

Film—If the standard 35-mm size is used, the initial cost is one-fourth that of paper, and storage requirements are one-sixth; duplication and development of records is relatively simple.

4.1.3. CLASS A-3 STATIONS. This includes a station whose site meets the specifications for a Class A station, but which has facilities for only one to three seismometers.

The housing should be large enough to include a three-seismometer operation. However, if available funds permit only one seismometer, it should be a short-period vertical, with paper recording facilities. If the station is to be a part of the seismological community, accurate timing, to within 0.1 to 0.2 second, is necessary. A precision pendulum clock or spring-driven chronometer is satisfactory, provided that it is adjusted properly and radio calibrated at least once, and preferably four times, daily. Visual time calibration is recommended only if accompanied by automatic recording of radio time marks on the record.

If funds permit operation of three seismometers, one short-period vertical, as described above, and two intermediate-period horizontal seismometers (T_0 = 4 to 8 seconds, T_g = 2 to 4 seconds) are recommended. In addition to the S waves of most earthquakes, the intermediate-period instruments are sensitive to ocean-generated microseisms. Recommended instruments are the Wilson-Lamison horizontal, the Wood-Anderson intermediate-period horizontal (which is direct recording), or the Sprengnether intermediate-period horizontal. Stations now using this combination include the South Pole (until January 1963) and Marie Byrd Stations in Antarctica, and the station in Fayetteville, Arkansas.

4.2. CLASS B STATIONS

These stations have peak sensitivity in the period range from 0.5 to 2.0 seconds, and peak magnification up to 150,000. They have the same characteristics as Class A stations except that background noise lowers their peak sensitivity.

Instruments:

(1) Same as A-2 or A-3 except that the short-period instruments have lower magnification.

(2) Wilson-Lamison MC seismometer, an inelegant and low-cost instrument. It uses the same galvanometer as is used in Class A stations: T_0 = 1.0 second, T_g = 0.5 second.

4.3. CLASS C STATIONS

These stations have peak response to periods 0.5 to 2.0 seconds, and peak magnification up to 25,000.

Instruments:

(1) Same as under A_2, A_3, or B, except at lower magnification.

(2) Wilson-Lamison vertical or vertical and horizontal MC seismometers.

(3) Sprengnether MC short-period vertical or vertical and horizontal seismometers. These can be operated in an industrial area if the foundation of the building where they are installed is satisfactory. Damping is provided by a metal plate moving in a magnetic field. $T_0 = 2.0$ second or more; T_g is chosen to match the seismometer.

4.4. SPECIAL PURPOSE SEISMOGRAPH STATIONS

4.4.1. THE LISTENING POST STATION. This is a proposed station adapted to a seismic area, especially along an active fault. Its purpose is to monitor the pattern of fault activity before, during, and after earthquakes. Instrumentation should be that for a Class A-2 or Class B station; also provision should be made for continuous recording on magnetic tape of ground frequencies from 0.1 to 100 cps in four dynamic ranges of the lower frequencies. This includes output on six channels from a strong motion seismograph, three channels for acceleration and three for ground displacement. In the high magnification range, frequencies of 1 or 2 cps and higher are to be taken from deep enough underground to avoid local wind or culture noise. Additional pickup of microtremors along the fault with telemetering to the main station should be provided. In addition, capability for intermittent recording of all sounds in the audible range and higher should be available.

4.4.2. THE UNMANNED SEISMIC OBSERVATORY. A posible treaty on a moratorium of nuclear explosions may include the installation of a number of portable seismographs in unfriendly territory, with a provision for an inspection of these stations at limited intervals, say once a month. Several versions have been suggested:

(1) A limited number of "Geneva" stations, in enemy territory, each surrounded by outposts or satellite stations equipped to telemeter seismic signals, continuously or on demand, to the parent station, the outstation to be in the form of a tamper proof box ("tamper proof," as used here, means only that any tampering whatever will leave telltale marks).

(2) The same as in (1) except that signals from the outpost are recorded locally on a long-duration recorder.

(3) The same as in (2) except that there is no parent station; only the outpost stations on unfriendly territory are permitted, with a provision that the records may be changed at stated intervals, say once a month.

An early proposal was that the outpost seismometers record on, say, 6-hour loops, and that information on the loops be broadcast on demand by telemeter. Six seismometers were to be provided, three components each of long- and short-period ones.

A recent suggestion provides recording the output from six seismometers on magnetic tape traveling at the rate of 0.02 ips. This permits 30 days of record on a 14-inch roll of tape. If this method is to be successful, accurate unattended time control is necessary. But if present-day long- and short-period seismometers, a time standard, 14-inch magnetic tape transport, and the necessary batteries are all to be contained in a box, that box could hardly be classed as portable. However, if the seismometers are condensed to the size of Willmores or the moon seismometers, and if the electronics are likewise condensed, which is within reason, the longest dimension of the black box need not exceed 100 cm, which is the longest dimension of the tape transport. Down-hole long-period seismometers are in the design stage. If they are developed, then there will be some hope of a six-component 30-day seismograph which can be housed in a fairly small container.

If specifications are less demanding, the components of a 60-day portable seismograph are now available. If the short-period vertical is sufficient, recommended instrumentation includes (1) a magnetically suspended seismometer, or some other seismometer with a temperature-compensated suspension; (2) a 60-day Autocorder driven by an electronic time standard modified to compact dimensions; and (3) a 28-volt "Nicad" battery, with a windcharger nearby to supply power. Each additional seismometer requires an additional recorder and more power, but not an additional time standard.

5

CAPABILITIES OF SOME SENSITIVE SEISMOGRAPH STATIONS*

Detection capabilities of certain of the well known sensitive seismograph stations will now be reviewed. Since we are for the most part interested in earthquake magnitudes of 4.5 to 5.5, discussion here will be limited to events in this range. However, before proceeding further, it should be pointed out that the large number of methods of assigning magnitude has led to considerable confusion. Magnitudes reported by regular observatories are generally derived from surface-wave amplitudes. VELA UNIFORM participants have used the so-called uniform magnitude, which in practice is derived mainly from the maximum amplitude in the first few cycles of the P wave and should more properly be called body-wave magnitude. A cross check of

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*This section was prepared by J. N. Jordan and D. W. Gordon, geophysicsts, U. S. Coast and Geodetic Survey.

a large number of earthquakes has revealed that magnitudes reported by independent observatories are often 0.5 to 1.0 units higher than the assigned uniform magnitudes reported by VELA UNIFORM participants.

The determination of the smallest earthquake which would be detected by a given station at a given epicentral distance is very complex. An approximate answer can be obtained by comparing the expected amplitudes extrapolated from the depth-distance (Q) tables with minimum readable amplitudes compatible with the response curve of the particular instrument. This answer can then be checked by examining the station bulletins for reading from earthquakes of known magnitude. However, cross checking reveals that the apparent sensitivity of a given station varies with azimuth to the epicenter as well as with distance.

A statistical analysis of this problem has been performed at the Wichita Mountains Observatory (WMO), a highly sensitive Class A-1 array station. As Figure 30 shows, WMO detected

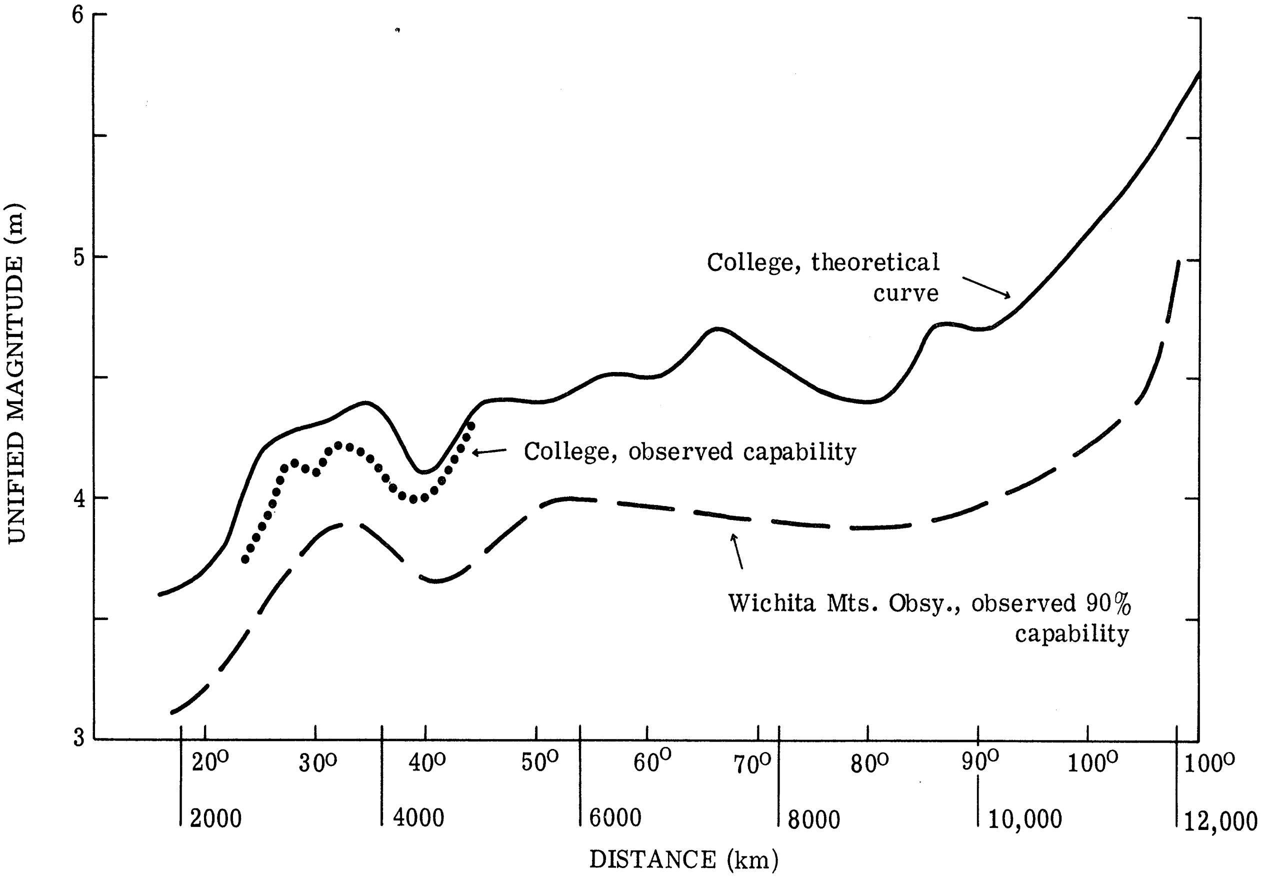

FIGURE 30. LOWER LIMIT OF P-WAVE RECEPTION AS A FUNCTION OF MAGNITUDE AND DISTANCE

90% of the earthquakes with unified magnitudes falling above the dashed line. The curve is fairly flat between about 50^o and 90^o, and WMO can detect 90% of magnitude 4.0 earthquakes in this range. Over its entire length the WMO curve is roughly parallel to the theoretical lower limit of earthquake detectability for College, Alaska, which is shown by the solid curve in the figure. The theoretical limit was based on Q values for shallow earthquakes, the instrumental response curve, and a signal-to-noise ratio of 2 to 1. The dotted line in the figure represents College observations of Kamchatka earthquakes between 1953 and 1960.

To obtain a statistical appreciation of the relative capability of sensitive network stations, about 130 earthquakes were selected for study from the Bulletin Central International Séismologique (BCIS) for 1959. The earthquakes were evenly distributed in the magnitude range from 4.5 to 5.5, and widely scattered geographically. The list of station readings for each earthquake was examined for P-readings from ten well known sensitive stations. These stations and pertinent data relative to their instrumentation are listed in Table 1. The scatter of the magnitudes quoted in BCIS for a specific earthquake was often as great as one unit; in many cases the magnitude was determined by only one station. Another troublesome aspect of the data is that the earthquakes

TABLE I. STATIONS CONSIDERED IN SENSITIVITY STUDY

Station	Seismometer	T_0 (seconds)	T_g (seconds)	V_m (km)
College, Alaska	Benioff MC	1.5	0.5	425
Eureka, Nevada	Benioff MC	1.1	0.6	425
South Pole, Antarctica	Benioff MC	1.6	0.5	100
Charters Towers, Australia	Benioff VR	1.0	0.2	120
Lwiro, Congo	Benioff VR	1.0	0.2	100
Matsushiro, Japan	Benioff VR	1.0	0.2	110
Kiruna, Sweden	Grenet-Coulomb	1.4	0.7	11
Tamanrassett, Algeria	Grenet-Coulomb	1.8	0.8	47
Resolute, Canada	Willmore	1.0	0.3	300
Pruhonice, Czechoslovakia	SVSN	1.0	1.5	36

All Seismographs are short-period vertical

T_0 = Seismometer period

T_g = Galvanometer period

V_m = Maximum magnification $\times 10^3$

which are assigned magnitudes are not evenly distributed geographically. For instance, the magnitude of earthquakes to South America is seldom reported for events of less than magnitude 6. This problem should be alleviated in the near future when a program being planned by the Coast and Geodetic Survey becomes operational. This program calls for routine publishing of magnitudes determined at the standard stations of the World-Wide net, in conjunction with the present reports of arrival times.

Figure 31 shows the results of the BCIS search for eight stations that have reported a reasonably adequate amount of data. To minimize the effect of the variation of sensitivity with distance, the graph is limited to data for the distance range from 50^o to 90^o. The figure indicates the expected general correlation between sensitivity and instrument magnification. It must be noted that the percentages of positive results depend not only on the mechanical capability of

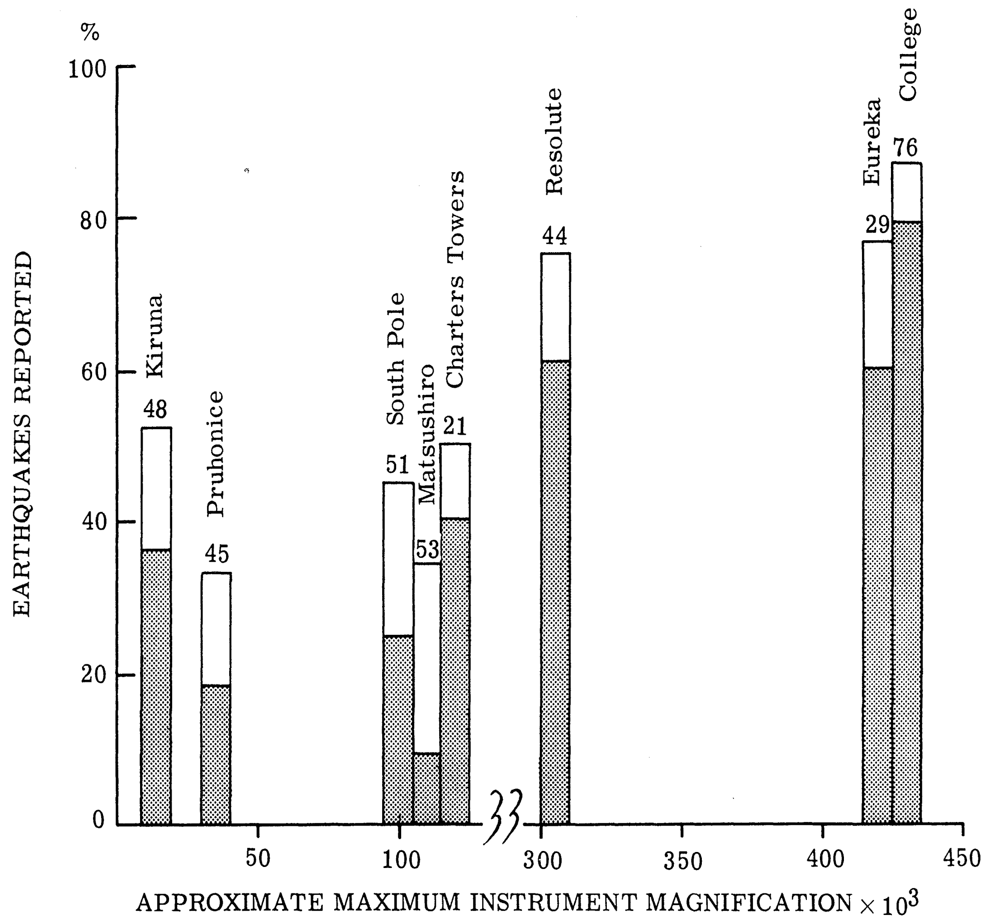

FIGURE 31. P READINGS REPORTED IN DISTANCE RANGE FROM 50 TO 90 DEGREES.

44 Total No. of Events Considered
☐ Magnitude Range 4 1/2—5 1/2
▨ Magnitude Range 4 1/2—5

the seismographs but also on the efficiency of the reporting system. The results indicate that stations of the quality of Eureka, College, and Resolute report P readings for about 60% of the earthquakes between magnitudes 4.5 and 5, for epicentral distances between 50° and 90°. On the other hand, stations operating at about 100,000 magnification detect only about 20% to 40% of such earthquakes.

Figure 32, a frequency polygon with 10° increments, shows the percentage of reported readings for magnitude 4.5 to 5.5 earthquakes over the entire P range. Similarly, Figure 33 shows the percentages reported in the magnitude range from 4.5 to 5. The dashed line represents the combined data from Eureka, College, and Resolute; the solid line represents the combined data from the other seven selected stations, which operate at considerably smaller magnifications. The extreme maximum and minimum, shown by the dashed line, are probably strongly weighted by anomalous reception of earthquake data at certain distances or from specific areas. The minimum between 30° and 40° represents data from California and Nevada events recorded at College and Resolute; the high peak between 60° and 70° depends almost entirely on College and Resolute readings. However, it is interesting that the combined data from the seven stations also show a zone of maximum sensitivity between 60° and 70°.

Table 2 contains a similar analysis of P-wave data from three nuclear explosions, all having a unified magnitude of approximately 5. In general, the table indicates positive results. Five of the stations recorded all of the events, and of the 21 possible readings in the P range, only two were missed. Unfortunately, no data were available from Tamanrasset. However, this station probably recorded at least two of the three events. The data presented here apparently indicate that reception is better for nuclear tests than for earthquakes. This may be due in part to the different method of computing magnitudes; i.e., earthquake magnitudes quoted in the BCIS are generally determined by surface-wave amplitudes, and the magnitudes given for the explosions depend largely on measurements of the P wave alone.

Conclusions in this section are based on incomplete data. As expected, however, a station's detection capability is roughly parallel to the sensitivity of the seismograph, which in turn is governed by the level of background noise or on the station's ability to reduce that noise. The problem is further complicated by evident lateral and vertical inhomogeneities deep within the earth.

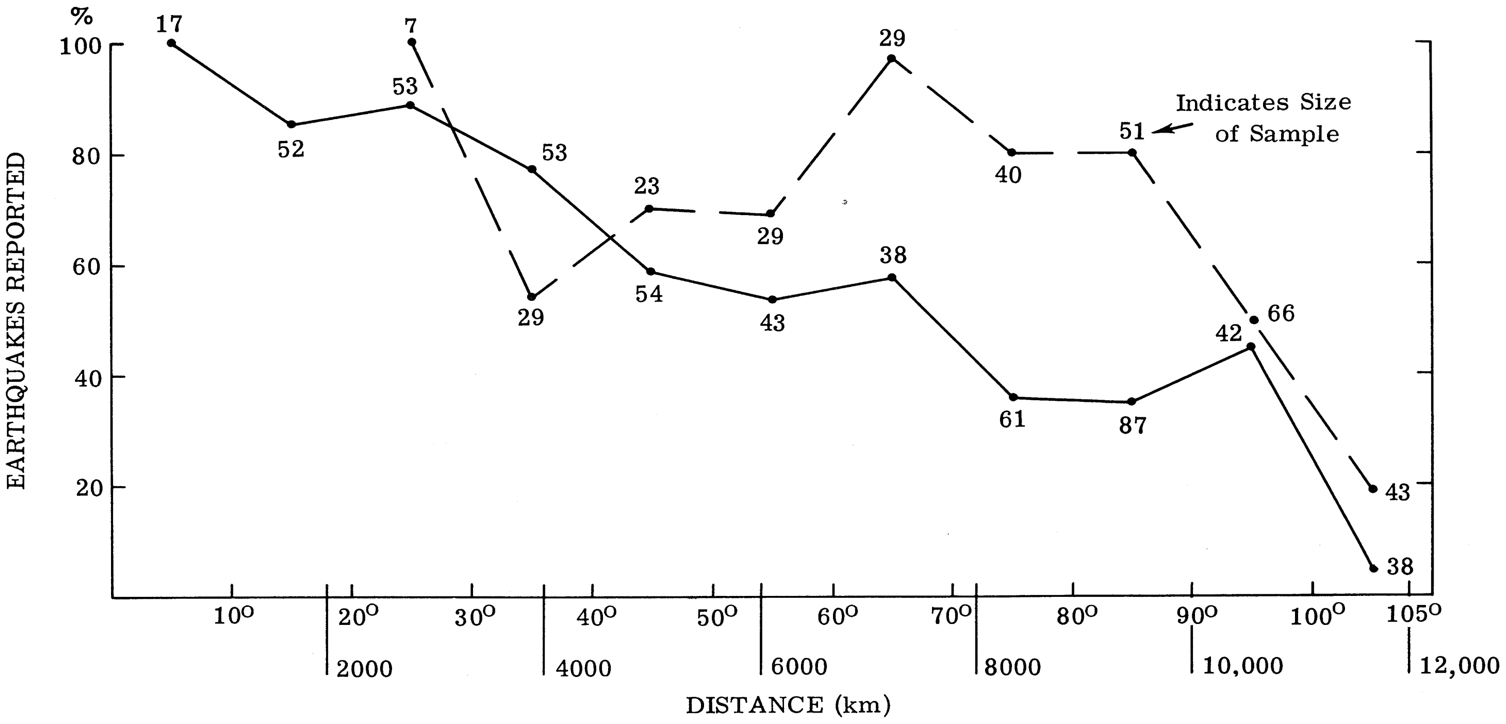

FIGURE 32. P READINGS REPORTED FOR EARTHQUAKES OF MAGNITUDE FROM 4.5 TO 5.5.

——— Kiruna, Matsushiro, Pruhonice, Tamanrasset, Lwiro, Charters Towers, South Pole

— — — College, Eureka, Resolute

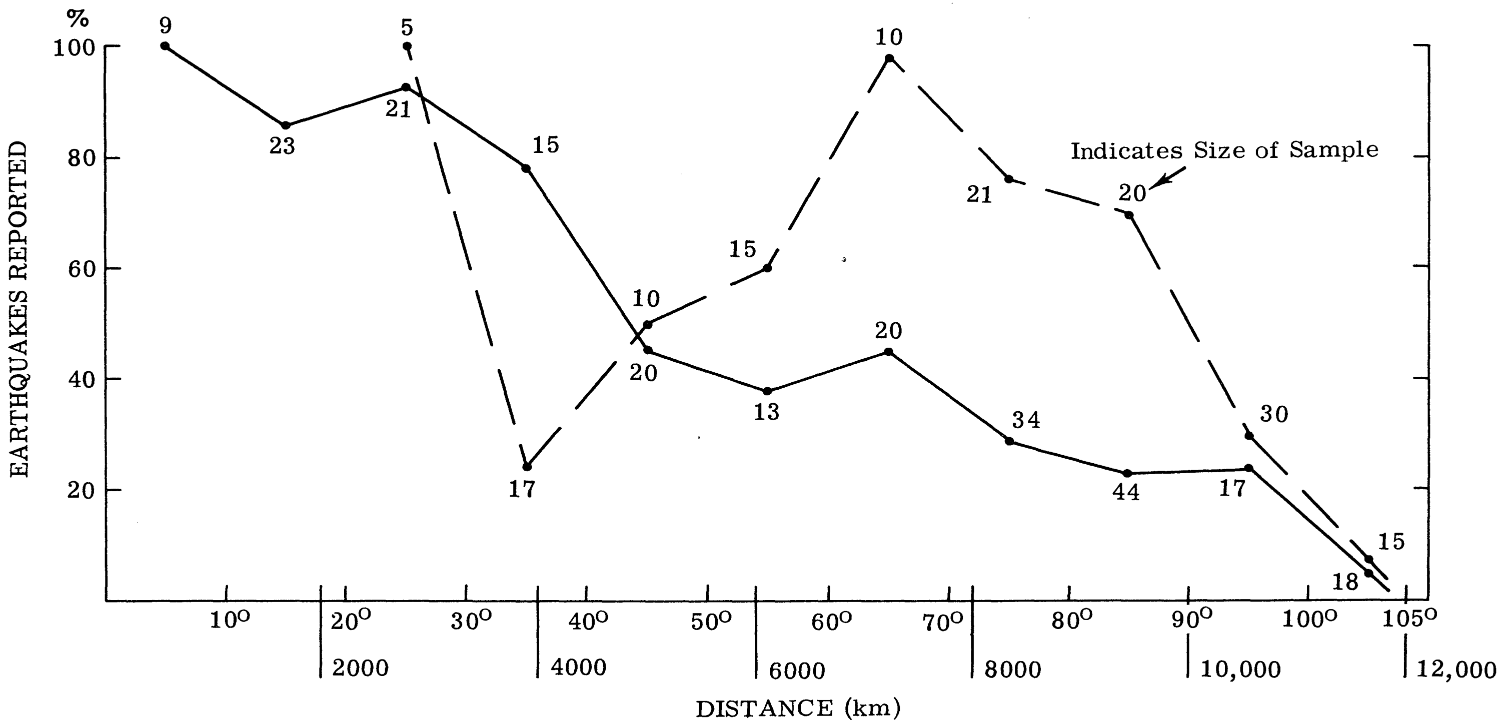

FIGURE 33. P READINGS REPORTED FOR EARTHQUAKES OF MAGNITUDE FROM 4.5 TO 5.0.
———————— Kiruna, Matsushiro, Pruhonice, Tamanrasset,
Lwiro, Charters Towers, South Pole
— — — College, Eureka, Resolute

TABLE II. ANALYSIS OF SEISMIC SIGNALS FROM THREE EVENTS

	SAHARA - May 1, 1962				SEMIPALATINSK - Feb. 2, 1962				HAYMAKER - June 27, 1962			
	Distance (degrees)	Signal	Ground Amplitude (mμ)	Ground Period (seconds)	Distance (degrees)	Signal	Ground Amplitude (mμ)	Ground Period (seconds)	Distance (degrees)	Signal	Ground Amplitude (mμ)	Ground Period (seconds)
College	89	+	2	0.7	60	+	76	0.8	34	+	38	0.9
Charters Towers	144	+	(PKP)		93	-			108	-		
Eureka	96	+	6	0.7	90	+	34	0.6	3	+	Off record	
Kiruna	45	+	125	0.8	33	+	580	0.8	78	+	27	0.6
Lwiro	35	+	*	*	67	+	*	*	132	-		
Matsushiro	104	-			48	+	*	*	80	+	*	*
Pruhonice	27	+	*	*	40	+	28	1.0	83	+	*	*
Resolute	69	+	5	0.9	62	+	*	*	39	+	*	*
South Pole	114	*	*	*	140	+	(PKP)		127	+	(PKP)	
Tamanrassett	2	*	*	*	61	*	*	*	99	*	*	*

\+ Readable signal
\- No signal
* No information available

Note: Ground amplitudes are measured 1/2 peak to peak.

6
SUMMARY

In summary, Table 3 will serve as a guide toward the selection of a site for a highly sensitive short-period seismograph station. If the locality of the station is limited to the physical environment near the institution operating the station, the table will assist in the selection of the site and the most suitable instrumentation.

TABLE III. RECOMMENDED MINIMAL DISTANCES FROM SOURCES OF DISTURBANCE TO SEISMOGRAPH STATION—SHORT-PERIOD SEISMOGRAPHS

Source of Disturbances		Seismometer on Hard Massive Rock, Granite, Quartizite, etc.			Seismometer on Hard Clay Hardpan, etc.		
		A	B	C	A	B	C
		km	km	km	km	km	km
1. Oceans—a. with coastal mountain systems as Pacific North and South America		300	50	1	300	50	1
b. with broad central and coastal plains as eastern North and South America		1000	200	10	1000	200	20
2. Inland seas, bays, and large lakes—Great Lakes	a	150	25	1	150	25	1
	b	500	100	5	500	100	5
3. High waterfalls, cataracts or excessive flow over large dams, e.g.,Niagara, Grand Coulee Dam	c	40	10	5	50	15	5
	d	60	15	5	100	25	10
4. Transcontinental oil or gas pipe lines, etc.	c	20	10	5	30	15	5
	d	100	30	10	100	30	10
5. Small lakes	c	20	10	1	20	10	1
	d	50	15	1	50	15	5
6. Reciprocating power plant machinery, rock crushers, heavy machinery, etc.	c	15	3	1	20	5	2
	d	25	5	1	40	15	3
7. Low waterfalls, rapids of a large river, intermittent flow over large dams	c	5	2	0	15	5	1
	d	15	3	1	25	8	2
8. Railways, if frequent operation	c	6	3	1	10	5	1
	d	15	5	1	20	10	1
9. Airports and airways having heavy traffic		6	3	1	6	3	1
10. Non-reciprocating power plant machinery, balanced industrial machinery	c	2	0.5	meters 100	10	4	1
	d	4	1	200	15	6	1
11. Busy highway—nearly continuous traffic or mechanized farm area		1	meters 300	100	6	1	meters 500
12. Graded country roads, high buildings		meters 300	200	50	2	1	500
13. Low buildings and high trees, wind charger for seismograph batteries if coupled to ground		100	30	10	meters 300	meters 100	50
14. High fence, low trees, large rocks, high bushes		50	25	5	100	50	10
15. Wind charger for seismograph batteries if decoupled from ground		30	15	5	60	30	10

a.—as in 1a
b.—as in 1b
c.—Source and seismometer on widely different formations, or that mountain ranges or alluvial valleys intervene.
d.—Source and seismometer on same formation and with no intervening alluvial valley or mountain range.
A—Gain for 1 cps 200,000 or more; B—Gain 50,000 to 150,000; C—Less than 25,000

The distances in the table are based largely on the experience of the writer or on material from available literature, and are subject to modification according to local needs or to regional physical conditions. The table applies to two types of subsurface conditions: (a) granite, massive limestone, quartzite, or basement complex, and (b) hardpan, caliche, or firm clay in an alluvial area. Less firm alluvial material is not considered; subsurface rock such as shale, volcanics, and loosely consolidated sandstone is intermediate between (a) and (b). An additional subdivision is made on the basis of homogeneity or inhomogeneity of the formations between the noise source and the station.

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ATTN: Rev. Daniel Linehan, S. J.

Xavier University
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THE REQUIREMENTS OF A HIGH-SENSITIVITY SEISMOGRAPH STATION by Dean S. Carder. A VESIAC State-of-the-Art Report. Oct. 63. 64 p. incl. tables, 36 refs.
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