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Research Directed Toward the Use of Long and
Intermediate Period Seismic Waves for the Identification of
Seismic Sources

by L. E. Alsop

Lamont Geological Observatory
Columbia University
Palisades, New York

Project No. 8652
Task No. 865203

Contract No. AF19(604)-7376

Final Report

July 31, 1964

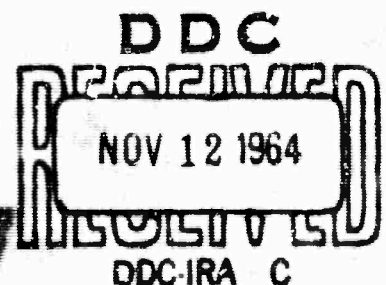
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OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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Abstract

A detailed account of the research accomplished as per the Statement of Work of this contract is given herein. Of particular interest to the needs of Project VELA-UNIFORM are the following: a study of the radiation patterns of surface waves from underground nuclear explosions and small magnitude earthquakes, wherein it was determined that the radiation patterns from explosions in tuff and alluvium, but not in granite, could be interpreted as arising from an explosive force acting as a step function in time; a study of the relative excitation of surface waves by earthquakes and underground explosions, which yielded the result that most but not all of the earthquakes studied generated surface waves 5 to 10 times greater than the maximum observed for explosions of the same Richter magnitude; an almost complete summary of Rayleigh wave phase and group velocities for various regions of the world; a program of epicenter relocation carried out so far for the South Pacific Ocean, the Arctic north of 60°N, the Gulf of Aden, Red Sea, and Arabian Sea, the African Rift Zone, and the Central Indian Ocean, which showed that in these places at least large earthquakes are confined to much smaller regions than previously thought; successful utilization of displacement transducers with long period seismometers, thereby improving the long period response of these instruments by removing the 6 db/octave fall-off with increasing period, which is inherent in velocity transducers.

At present, the current Statement of Work for this contract reads as follows:

The Contractor shall supply the necessary personnel, facilities, services and materials to accomplish the following:

Item 1 - Extension of existing seismograph pier to accommodate the more sensitive, longer period seismological instrumentation required to carry out the research herein.

Item 2 - Investigation of the applicability to intermediate (2 to 10 sec) and long (10 sec and greater) period seismic waves of phase compensation techniques for the purpose of determining an effective source polarity as a function of azimuth. In this connection the compilation of world-wide charts or tables of phase and group velocity for surface waves of various periods will be initiated.

Item 3 - Development of high-speed computational techniques for the solution of the normal-mode propagation problems and the Fourier analysis and synthesis problems that arise in connection with Item 2.

Item 4 - Development of seismic instrumentation with increased sensitivity in the long period range and with improved discrimination against noise in the dominant microseism band.

Item 5 - Conduct studies and develop techniques in the use of specialized instrumentation for seismic data recording and analysis. Included would be investigations of tape recording systems, filtering, digital analysis and analogue computers for the purposes of improving detection techniques and methods of analysis of seismic records.

Item 6 - Conduct tests to increase the knowledge of crustal structure by land refraction methods. Field studies, using a portable seismic recording system, will be conducted at selected sites.

Item 7 - At a site to be designated by the Contracting Officer, establish a long period seismograph station to form, with the existing Palisades and Waynesburg Stations, a tripartite array for basic studies of body and surface waves. An additional station within the large array may be established to form a smaller inner array if these studies indicate it to be advantageous.

Item 8 - Develop techniques for analyzing microseismic data and conduct studies of the microseismic spectra.

Note 1 - In the performance of the above research, the contractor will continue to operate the widely distributed network of long and intermediate period seismic stations that were initially put into operation in connection with the International Geophysical Year, with such changes in numbers, location, or instrumentation as may be deemed desirable for the performance of the contract.

The work accomplished under each item will be described in detail in the bulk of this report.

Item 1 - Extension of existing seismograph pier to accommodate the more sensitive, longer period seismological instrumentation required to carry out the research herein.

Bids were obtained for extending the seismograph pier, and also for building a small additional pier at another location on the

Lamont grounds. It was determined that the second alternative was far less costly, and accordingly the small additional pier was constructed, and is in use for long period seismographs.

Item 2 - Investigation of the applicability to intermediate (2 to 10 sec) and long (10 sec and greater) period seismic waves of phase compensation techniques for the purpose of determining an effective source polarity as a function of azimuth. In this connection the compilation of world-wide charts or tables of phase and group velocity for surface waves of various periods will be initiated.

A. Radiation Patterns

A paper, entitled "Radiation Patterns of Surface Waves from Underground Nuclear Explosions and Small Magnitude Earthquakes" by James N. Brune and Paul W. Pomeroy, was submitted to the Journal of Geophysical Research.

In this paper, the radiation patterns of surface waves were used to study the source mechanisms of underground nuclear explosions, associated collapses and small magnitude earthquakes. This study is the first successful attempt to use the technique of Fourier analysis and phase equalization as a function of azimuth to study the source mechanisms of underground nuclear explosions. The results are important to the problem of distinguishing underground nuclear explosions from earthquakes on the basis of seismic wave generation as well as to the problem of determining earthquake source mechanisms. The successful application of the techniques used in this paper for the study of explosion source mechanism, which in many ways is simpler to study than for earthquakes, indicates that with improved epicentral information,

better instrumentation and accurate regional phase velocity data, these techniques will ultimately yield extremely valuable information about the source mechanisms for earthquakes and explosions and about the tectonic strains within the earth.

In recent years, several authors have used surface waves to study source mechanism. However, because of a lack of a sufficient number of adequately equipped seismograph stations, the method has not been fully utilized. The temporary LRSM (Long Range Seismic Measurements) stations, established to monitor the underground nuclear explosions at the Nevada Test Site, operated long period instruments sharply peaked around 25 seconds, and often clearly recorded the fundamental mode of Love and Rayleigh waves in the period range from 10 to 30 seconds. Thus they provide an excellent source of data for the study of the source mechanisms of underground nuclear explosions, since they surround the test site and the horizontal instruments are oriented in radial and transverse directions to the test site.

Seismograms from these stations for the larger underground nuclear explosions and certain earthquakes were studied. Selected records were digitized and the digital records were then Fourier analyzed to determine amplitude and phase spectra. The phase spectra were then equalized to the source. The results of this analysis were studied as a function of azimuth for each event. The results were then interpreted in terms of possible source mechanisms.

It was concluded that:

1. The radiation patterns of Rayleigh waves generated by underground nuclear explosions in tuff and alluvium suggest that the

source mechanism is an explosive force acting as a step function in time. The time function agrees with that obtained by other authors from doubly integrated accelerometer records. However, the existence of Love waves and small asymmetries in Rayleigh wave amplitudes indicate that more complicated forces also act at the source for these events.

2. The collapses which follow many of the larger explosions in tuff and alluvium generate Rayleigh waves with reversed polarity relative to the explosions. The source mechanism could be an implosive force acting as a step function in time (or a downward force acting as a step function in time). Love wave generation by the collapse events is extremely small compared to that by the explosions. This fact indicates that the generation of long period Love waves is a property of the source for the explosions, and is not a result of mode conversion along the propagation path.

3. The explosion in granite (Hardhat) produced a surface wave radiation pattern with nearly perfect double-couple symmetry in both phase and amplitude. Such a pattern could not be generated by a simple explosive force and must have been caused by cracking, forced motion along pre-existing faults, or by tectonic strain release due either to release of strain in the volume of rock shattered by the explosion or triggering of tectonic motion along nearby faults.

4. The amplitude and initial phase spectrums of Rayleigh waves from earthquakes are usually more complicated than the spectrums of Rayleigh waves from the explosions in tuff and alluvium. The radiation pattern of surface waves for the Arizona-Utah border earthquake of 15 February 1962 showed an initial phase of about zero for

Rayleigh waves at all azimuths for which it was possible to make reliable measurements. This is opposite in phase to the phase observed for the explosions in tuff and alluvium. It is expected that the radiation patterns for Rayleigh waves generated by earthquakes will be quite different from the radiation patterns for explosions in tuff and alluvium and the results of this study indicate that in the future it will be possible to use the method described here to study the source mechanisms of numerous earthquakes.

B. Spectral Analysis of Body Waves and Synthesis of Time Function

A method to compute the excitation time function at the origin has been developed. This method consists of the following processes:

1. The instrumental characteristics of an electromagnetic-seismograph have been computed and the effect of the instrument may be removed from a spectrum of a recorded body wave. A true ground motion is thus obtained.

2. It is known that the spectrum of the ground motion of a body wave consists of two parts, a spatial spectrum $S(p)$ and a time spectrum $F(p)$. A mathematical expression for the spatial spectrum may be derived for a spherical origin.

By removing the spatial spectrum which is computed under an assumption of a double-couple type stress distribution from the spectrum, the time spectrum $F(p)$ can be obtained from a spectrum of an observed ground movement. Finally, the time function is synthesized by means of numerical integration.

Synthesized time functions have been computed for 12 earth-

quakes (4 shallow earthquakes, 8 deep-focus earthquakes). It is found that the time functions of deep-focus earthquakes begin with a sharp commencement and die out very gradually, or look like step functions, as expected. The time functions of shallow earthquakes are generally more complicated; most of them show a doublet type of variation and some of them are even more oscillatory.

This difference of the time functions between shallow and deep-focus earthquakes implies that the effect of the free surface has an important role for the shallow earthquakes. To study this problem, the reflection of the waves caused by a free surface near the origin is taken into account for the computation of a time function of a shallow-focus earthquake. It is found that some of the time functions of shallow earthquakes become very similar to those of deep-focus earthquakes when the reflection caused by a free surface is removed.

Presumably we may conclude that there is no essential difference in the mechanism of the strain release for shallow and for deep-focus earthquakes except for some major shallow earthquakes where it was impossible to obtain a simple time function even if a free surface reduction has been done.

Also, an attempt to compute a time function of an explosion has been made (Hardhat, February 15, 1962). The synthesized time function is also not simple in this case. It is believed that the frequency range in this analysis is higher than for the previous analyses and, accordingly, minor structure of the crust has an important effect on the free surface reduction. It is difficult to make an accurate discussion of the excitation function of an explosion unless we know an exact free surface reduction.

C. General Summary of Phase Velocity Mapping Project

Rayleigh wave phase velocities are generally determined by the following methods:

1. Tripartite-net method by correlating the same phase in a three-station net.
2. Two-station correlation method by selecting at least two stations which lie approximately in a common great circle with the epicenter. The wave front is assumed to be perpendicular to the great circle path.
3. One-station method by assuming the initial phase to be independent of the frequency at the origin.

Phase velocities thus determined by many investigators in various parts of the world provide the principal data for the present report. Maps have been prepared in the forms of regional velocity maps and velocity-contour maps.

a. Eurasia-Africa

The phase velocity values, which we have obtained for this region, are determined by means of the two-station correlation and the one-station methods. They have long paths across several geological or physiographical provinces. However, the phase velocities through Tibet and Himalaya are lower than those for the paths across the northern part of USSR. The phase velocities for Africa correspond to standard continental structure, i.e. about 35 km in the crustal thickness. These average phase velocities give only a gross picture of the average structure for the wave propagation paths.

Phase velocities have been measured by the tripartite-net method in the Alps and Mediterranean by Knopoff and Press. Their data, which were determined chiefly from Atlantic earthquakes, are used in our regional velocity map as these waves show less interference.

b. Pacific Ocean

Kuo, Brune and Major used the one-station and two-station correlation methods to determine phase velocities for fourteen paths across the Pacific centered at Suva. Pomeroy determined the phase velocity between Bikini and Eniwetok. Rayleigh wave phase velocities for the paths through the northern Pacific in the deep ocean basins are definitely higher than for those paths across the southeastern Pacific, where the Easter Island Rise is situated. Phase velocities are much lower for those paths across the Melanesian and Tasman-New Zealand tectonic complex.

c. New Zealand

Thomson and Evison published their phase velocity data for North Island and the northern part of South Island in the period range from 20 to 30 seconds. Their preliminary results seem to indicate that phase velocities are quite uniform in this part of New Zealand.

d. Japan

Aki's phase velocity determination by the tripartite-net method in Japan for the period of 29-second Rayleigh waves gives a good correlation between topography and phase velocity. Low phase velocity coincides with the higher elevation in Japan.

e. South America

This study is still in progress at Lamont. Phase velocities

in South America are chiefly determined by the two-station correlation method. The preliminary phase velocity data is consistent with respect to the geological provinces. The paths containing a large percentage in the Andes have lower phase velocities than those containing a small percentage in the Andes.

f. Eastern Canada

Brune and Dorman found phase velocities are relatively high in the Canadian shield area.

g. U. S. A.

The most complete data available, at present, is in the U. S. A. Ewing and Press in 1959 determined phase velocities across the United States by using a distant earthquake of Samoa in the Pacific. Their method was chiefly the tripartite-net method. Their work has been extended here to include the most recent data of the LRSM stations. In the present extension an Atlantic earthquake was used so that a reversed Rayleigh wave propagation pattern through the U. S. could be established. To determine the phase velocities in the Appalachian Mountain area, the Mexican earthquake of September 1962 was used, since there were six LRSM stations in operation at that time and these stations are approximately in a common great circle with the epicenter. In the Pennsylvania and New York area, phase velocities were determined by Oliver, Kovach and Dorman.

Our most recent results of phase velocities determined by both the tripartite-net and the two-station correlation methods, are in good agreement with these previous results published by Ewing and

Press and Oliver, Kovach and Dorman. The phase velocities are highest at the West Coast and lowest in the Basin and Range Province, Colorado Plateau, and Rocky Mountains. The phase velocities become higher, in comparison with the high land toward the east in the Interior Plain, and again decrease along the Appalachian Mountains.

With these data, velocity-contour maps of the United States were constructed at 5-second intervals for 20, 25, 30, and 35-second Rayleigh waves.

Detailed studies of the crust and upper mantle structure of the United States were made along two profiles across the continent on the basis of the phase velocity data, seismic refraction data and gravity. These two profiles are (1) from Southern California through Arizona, New Mexico and Tennessee to the Southern Appalachians, and (2) at the northern part of the United States extending from San Francisco through the Basin and Range Province, Rocky Mountains, and the Interior Plains to New York.

The phase velocity data support the existence of the intermediate layer in the crust, which is in general identified by second arrivals in the seismic refraction method. Nevertheless, for the Pennsylvania and New York area and for the west coast of California, the assumed one-layer structure also fits the observed data. This demonstrates that the structure interpretation is never unique.

Item 3 - Development of high-speed computational techniques for the solution of the normal-mode propagation problems and the Fourier analysis and synthesis problems that arise in connection with Item 2.

A. Travel Times, Body Waves and Dispersion in the Earth

A simple relation between body waves and higher mode dispersion has been derived, based on a constructive phase interference requirement for body waves such as S_H and PS. For a normal mode, the travel time, tt , for a given distance, Δ and phase velocity, $1/(dt/d\Delta)$, are related to the period, T , by the equation:

$$tt - \Delta (dt/d\Delta) = n + \phi / 2\pi T$$

where n is an integer equal to the mode number minus one, and ϕ is a phase shift arising from reflection and propagation of the wave. The group velocity is given by $\Delta / (tt - (\frac{d\phi}{d\omega})) = \text{const}$. For a homogeneous sphere ϕ is the phase shift for reflection from a spherical surface. ϕ (and T) may be experimentally determined from the difference in phase of Fourier transforms of successive surface reflections of body waves corresponding to rays of a given phase velocity (e.g. ScS at one station and ScSScS at another station at twice the distance). The method may be used to measure torsional dispersion from S_H and $S_H c S_H$ waves and, over a limited phase velocity range, spheroidal dispersion from PS waves.

The discovery explains very simply the relationship between body waves and higher normal modes and thus adds greatly to the understanding of wave propagation in the earth.

Experimental values of dispersion are given for several values of phase velocity (8 to 36 km/sec) and modes from 3 to more than 10 and compared with theoretical values.

3. Calculation of Free Periods of Oscillation

Two programs for the IBM 7090 have been completed for the study of the free oscillation of the earth. One program computes the periods of the free vibrations for earth models consisting of a solid mantle and a liquid core. The other program has provision for treating earth models with a solid inner core. In addition, both programs compute phase and group velocities and the amplitudes of radial and transverse particle motions and the gravitational perturbation as a function of depth.

The free periods and resulting phase velocities have been calculated for all orders with free periods greater than 200 seconds for the fundamental and first and second higher modes for four earth models. The four models used were obtained by combining compressional and shear velocities according to Jeffreys or according to Gutenberg with either Bullen's density model A or B. The Bullen B model used differed from that originally proposed by Bullen in that the inner core was assumed to be liquid.

With these data it is possible to obtain theoretical phase velocity curves for long period surface and mantle waves above 200 seconds. With increasing period these waves become less and less dependent on crustal variations and therefore it is much easier to determine the source mechanism. Unfortunately, in this case theory is ahead of observational data and must wait for more sensitive long period seismographs.

The effect on the free periods of introducing rigidity into the inner core has also been studied. The core modes are very sensitive

to the rigidity of the inner core, decreasing rapidly in period with increasing shear velocity of the inner core. However, there is very little effect on the normal types of spheroidal vibrations, except when the period is close to that of a core mode. Under these circumstances an interaction occurs between the two modes in which the vibrations take on characteristics intermediate between the two modes, and an appreciable shift in period occurs.

During the course of this investigation, several new modes of vibration have been discovered. One of these, a long period vibration of order number one, is very similar to the vibration proposed by Slichter to explain the period of 86 minutes obtained in the spectrum of free vibrations from the gravimeter record of the great Chilean earthquake of 1960.

C. Rayleigh Wave Phase Velocities at Very Long Periods

Spectral peaks corresponding to the free periods of oscillation of the earth have been found in the spectra of eight seismograms obtained from vertical seismographs located at various stations around the world. The stations are all part of the Lamont world-wide network of long-period seismographs initially placed in operation during the International Geophysical Year. The stations in question are located at Agra, India; Hallett, Antarctica; Hong Kong; Lwiro, Republic of the Congo; Mt. Tsukuba, Japan; Resolute, Northern Canadian Islands; Suva, Fiji; and Uppsala, Sweden. All of the data were obtained following the great Chilean earthquake of 22 May 1960. The vertical seismographs are all equipped with 15-second pendulums and 75-second galvanometers.

The records used started from approximately four to approximately fifteen hours after the earthquake occurred. In most cases the seismometers were driven off scale and were reset the following day when the records were changed. This is the primary reason for the different beginning times of the records. As much as possible of one complete day's record was used for the analysis.

The seismograms were digitized at Lamont. All of the records were digitized with an interval of approximately six seconds between data points. The exact value of the digitization interval was calculated to three decimal places by dividing the time length of the record by the number of data points. In this way allowance could be made for the stretching or shrinking of the record paper during processing.

Prior to digitizing, the records were smoothed by eye to remove extremely short period waves. After digitization, the data were smoothed by averaging over 19 and 21 points, and then every third point was selected in order to reduce the amount of the data while avoiding aliasing. The data were then Fourier analyzed and the periods of the spectral peaks obtained by interpolation.

The various spectra show the features to be expected. Since these are all the spectra of vertical seismograms, only the spheroidal types of oscillation are observed. The general appearance of each of the spectra is approximately the same. The rapid fall-off of the sensitivity of the seismograph at long periods limits the longest observed free oscillations to those with periods of about 600 to 700 seconds, that is, to approximately orders 8 and 9 of the fundamental mode. The shortest

period oscillations observed are of the order of about 200 seconds. As might be expected, the short period oscillations decay more rapidly with time than the long period oscillations. Therefore, the spectra of the seismograms starting many hours after the earthquake do not have peaks with as short a period as the spectra of seismograms starting a few hours after the earthquake.

The highest order observed for the first higher mode is possibly order 9. This is in accord with theoretical calculations which indicate that the amplitudes of orders 9 through 15 will be small at the surface of the earth.

The data discussed so far have been combined with all other free oscillation data available for the spheroidal oscillations to obtain average values for the periods of the free oscillations. There is a slight problem in choosing data about spheroidal oscillations. For orders 10 and below of the fundamental mode there can be no confusion in distinguishing spheroidal from torsional oscillations with the exception of S_7 and T_7 , so that all of the data available were used for these orders. For orders higher than 10 it becomes difficult to positively identify a spectral peak as belonging to a spheroidal or to a torsional oscillation. Accordingly, for orders higher than 10, only data obtained by vertical seismographs or by gravimeters, both of which record only spheroidal oscillations, were used.

The data selected in accordance with the above criteria in addition to that previously discussed were obtained by workers at Los Angeles; Pasadena; Palisades; Chester, New Jersey; Tiefenort, Germany; Trieste; Paris; and Kyoto. The data of the first four were used for

all orders, of the last four only for orders 10 and below.

Since the earth is neither homogeneous nor a sphere, and its elastic parameters and density vary azimuthally as well as radially, it is not to be expected that the periods of free oscillation will be the same at all stations. This may be seen intuitively by considering the free oscillations as standing waves which arise from the constructive interference of surface waves. Thus, if the great circle paths through the several stations differ, it can be expected that different periods of surface waves will constructively interfere along the different paths. Therefore, a systematic variation between stations should be expected, particularly for the shorter period oscillations which are confined to the crust and upper mantle. A comparison of the observed periods for the different stations with the average period does show this systematic difference at the shorter periods, that is, 200 to 350 seconds.

The phase velocities of Rayleigh waves can be calculated from the periods of the spheroidal oscillations. The phase velocities of course can be calculated only at the periods of the free oscillations. The actual curve, continuous from 200 to 3200 seconds, is obtained by interpolating graphically. Over much of the range the standard error of the mean is less than one part in a thousand.

For purposes of comparison, phase velocity curves obtained from the calculated free periods of oscillation for two earth models have been compared with the observed data. The models both have velocities according to Gutenberg but one has the densities of Bullen's model A, the other of Bullen's model B. For periods greater than 1000 seconds, the phase velocities calculated from the observed free periods

agree very well with those calculated for the Gutenberg-Bullen B model. For periods less than 1000 seconds, the observed phase velocity diverges from that of the Gutenberg-Bullen B model and tends toward the phase velocity curve of the Bullen A model, finally meeting the curve at about 550 seconds. The observed curve follows the theoretical curve for the Gutenberg-Bullen A model, at first slightly below, then slightly above until 350 seconds. The variations in this period range from the theoretical curve are only slight, but they are consistent and do not show any random character. Below 350 seconds the observed phase velocities diverge downwards from the theoretical phase velocities. Once again they approach the Gutenberg-Bullen B model but continue right through this phase velocity curve and near 230 seconds the observed phase velocities are lower than those calculated for either model. The observed phase velocities in the period range of 200 to 400 seconds are in excellent agreement with the values obtained from surface waves by Brune.

D. Short Period Seismic Waves

The propagation of short-period oceanic surface waves with predominant periods between 5 and 20 seconds was studied for a large number of paths in the Atlantic, Indian and Pacific oceans. In the ocean basins these waves are controlled largely by the sedimentary layer. The amplitudes of the short-period waves are greatly dependent upon the nature of the propagation path and on the properties of the source. Surface waves with periods between 5 and 10 seconds are often observed for paths that cross the continental margins of the Pacific, but are recorded only rarely for similar transmission paths in the Atlantic. Probably this

effect is due to the differences in the structural configuration of the margins, particularly to such differences in the sedimentary strata.

Seismic refraction and reflection measurements indicate that most of the oceanic paths for which the 5 to 10 second waves are observed are characterized by sedimentary thicknesses that do not average more than a few tenths of a kilometer. The predominant periods of the short-period wave train are increased to as much as 12 to 20 seconds for paths that traverse the thick sediments of the Argentine Basin. This increase in period, which was predicted theoretically for regions of relatively thick sediments, indicates that the low-rigidity sediments play a prominent role in determining the character of the short-period wave train. The increase in the predominant periods of the waves associated with the first Love and first shear mode also accounts for the absence of the 5 to 10 second waves in areas of thick sediments such as the continental margins of the Atlantic.

Dispersion data for the Rayleigh, first Love and first shear modes were used in conjunction with reflection and refraction results to estimate the average shear velocity in the sediments of the Argentine Basin. The average shear velocity in the upper 0.5 km of sediments is about 0.2 to 0.4 km/sec, and the velocity in the kilometer of sediments below this is about 0.5 to 0.7 km/sec. Sedimentary shear velocities of a few tenths of a kilometer per second were also obtained for paths along which the average sedimentary thicknesses are a few tenths of a kilometer.

For group velocities between 4.2 and 3.4 km/sec, the particle motion in the first shear mode is retrograde; ratios of horizontal-to-vertical motion as large as 3.5 are observed at island and coastal stations.

Seismic waves with periods of 10 to 30 seconds and with group velocities of 4.0 to 4.4 km/sec are sometimes recorded on the vertical components of long period seismographs. These waves may be explained as higher modes of the Rayleigh type. Oscillatory waves with periods of 5 to 10 seconds are observed to follow the P wave in many oceanic areas. These arrivals are attributed to a type of leaking mode that results from the multiple reflection of SV waves in a low-rigidity layer.

E. Epicenter Relocation

Seismicity studies were carried out for the following areas: the South Pacific Ocean; the Arctic north of 60°N; the Gulf of Aden, Red Sea and Arabian Sea; the African Rift Zone; and the Central Indian Ocean.

The method of precise epicentral determinations consists of relocating the epicenters of earthquakes using a computer program. A program written by Bolt (Geophysical Journal, 1960) has been modified for this study. More than 200 P and PKP readings were used for some of the larger earthquakes studied. All known earthquakes within the above regions were relocated for the period 1955 to 1962, with the exception of the South Pacific (1957 to 1963).

When previous determinations of epicenters were plotted on a map for the mid-oceanic ridges, it was found that the data scattered

over a belt approximately 200 to 500 km in width. After the epicenters were relocated, the data were concentrated within 50 km of the crests of the oceanic ridges. Much information concerning the geological structure, the position of the mid-oceanic ridge, and the existence of fracture zones can be learned from a study of precise locations of epicenters. In each of the areas studied, information was available for more earthquakes in the interval 1955 to 1962 than was available for the previous 50 years.

If these results are typical of seismic belts and of small shocks as well as large ones, this study is of considerable importance to the VELA program.

F. Study of the Deep Argentine Earthquake of December 8, 1962

1. Observed travel times for multiply-reflected ScS waves.

Multiply-reflected waves from the December 8, 1962 deep-focus earthquake in Argentina were recorded very clearly at stations of the Lamont IGY and USCGS standardized world-wide networks, and at Canadian stations. The data gathered from this earthquake for the multiply-reflected ScS and sScS were used to construct and to extend to shorter epicentral distances the travel times of these phases. The observations of the ScSScS, ScSScSScS, sScSScSScS and ScSScSScSScS have enabled us to obtain the travel times down to an epicentral distance of 90° . The existing tables so far show the travel time of ScSScS down to an epicentral distance of 90° only. A paper on this subject was presented at the Spring 1964 AGU meeting in Washington, D. C.

In the process of plotting the ScSScS travel times, a mistake

was found in the literature for the ScSScS travel times (Gutenberg and Richter, "Donnees Relatives a L'Etude des Tremblements de Terre a Foyer Profond", Publications du Bureau Central Seismologique International 1937, and in Richter, C., Elementary Seismology, Freeman & Co., 1958, p. 684.

2. Rigidity and Q factor determination

The S, ScS, sScS, ScSScS, sScSScS, ScSScSScS, sScSScSScS and ScSScSScSScS have been recorded very clearly at some of the IGY and USCGS stations around the world, and at Canadian stations. These phases have been digitized and, using a Fourier transform program for the IBM 1620, their spectra have been obtained. A program has been written for the same computer in order to obtain the path length of the body wave under consideration. This program uses a given velocity vs. depth distribution, and computes the path length. A program which calculates the reflection coefficients at the core-mantle boundary, and at the free-surface, is used in order to correct the observed spectrum of these phases. It has been found in the process of computing the absorption coefficient that there is an extra term, which has not been taken into account by Press, which arises from the geometry of the problem. For an ScS the geometrical factor for reflection at a spherical surface is divergent in nature, and it is independent of the physical properties of the material or wavelength. This same factor of reflection at a spherical surface is convergent in nature for the ScSScS and higher order reflections at the core-mantle boundary.

Multiply-reflected ScS phases (of the SV type) recorded at close stations are used in the calculation of the rigidity of the

outer-core of the earth. This calculation of the rigidity using stations at larger distances is under study.

3. Focal mechanism study

A fault-plane solution has been made using readings of compression and dilations of 36 stations around the world. Dr. Hodgson, of the Dominion Observatory, has run a fault-plane solution with a program for the IBM 1620, and he has obtained a fault-plane solution very similar to the one obtained by this investigator for the same earthquake of December 8, 1962, (a single-couple type of mechanism).

P and S waves at 11 stations were digitized and Fourier transforms were obtained for these phases. These spectra of P and S waves have been plotted and will be compared with spectra obtained for P and S waves from theoretical considerations applicable to a double-couple mechanism. The theoretical development has been carried out by Dr.

T. Matumoto, of Lamont Geological Observatory. Using the spectrum of the P and S waves, a radiation pattern for a given spectral component will be plotted versus azimuth, (Amplitude (T) vs. Azimuth). (Also, an amplitude (T) versus distance plot will be used to infer, if possible, how sharp the core-mantle discontinuity is.)

The spectrum of the P and S waves will be used, also, to ascertain any azimuthal effect on the spectral structure of these phases. Kasahara has done a study along this line; however, he did not have any conclusions as to the observed difference in spectral structure of the S phases. Ben Menahem has claimed that this difference may be due to a moving source.

G. The Characteristic Numbers of the Semi-Diurnal Earth Tidal Component for Various Earth Models

A study of the static deformation of the earth due to tidal-generating potentials to evaluate the possible cause for the discrepancy between the accumulated observational data of earth tides for the principal semi-diurnal tidal constituent, M_2 , and the theoretical values has been made. The characteristic numbers, h , k and ℓ of the earth have been calculated for earth models consisting of velocities due to Jeffreys or Gutenberg with Bullen A or Bullen B density distribution. The computations were made using a modification of an earlier program for an IBM 7090 written for calculating the free periods of the earth.

It is found that the characteristic numbers of the earth are nearly independent: (1) of the presence of the solid inner core for a wide range of the possible values of the outer-core rigidity; (2) of either the Jeffreys or the Gutenberg velocity models; i.e. of the presence or absence of a low velocity channel in the upper mantle. A comparison of the theoretical gravimetric factors G calculated for a continental and an oceanic earth model with the observed gravimetric factors of the semi-diurnal tidal constituent obtained principally during the International Geophysical Year indicates that the differences in the observed values of G appear to be primarily due to the effects of the ocean and only secondarily to differences in the variation of the crustal structures. There is virtually no effect due to the presence of the solid inner core.

H. PL Waves

A paper entitled "Dispersion and Attenuation of Leaking Modes"

by S. Su, J. Dorman and Jack Oliver is nearing completion. This paper describes a study of elastic waves corresponding to the fundamental and higher leaking modes in the continental crust-mantle waveguide. The approach is both theoretical and experimental. The theory is based on Haskell's (1962) matrix formulation for motion at the surface of a layered half-space as a result of a body wave incident on the layers from the half-space. A method is developed for obtaining dispersion curves and attenuation for waves of the leaking mode type. Theoretical curves and attenuation computed by this method for a number of earth models are then compared with dispersion and attenuation data of Oliver (1964) and with some new data for certain paths in South America. Theoretical values of attenuation for simple earth models are in reasonable agreement with that measured for PL propagation across the United States by Oliver (1964). Theoretical curves are consistent with data for waves of the PL type and of the shear-coupled PL type. In particular, it is demonstrated that dispersion data for the shear-coupled PL waves are of special value for a more refined determination of earth structure. Furthermore, certain waves which appear to be associated with at least two higher leaking modes were discovered. The identification of extended wave trains in the portion of the seismograms between the P and S waves for shocks at moderate epicentral distances with the leaking modes offers the hope that substantial portions of many seismograms can be explained in this manner.

I. Spectra of Body Waves

The nature of the spectrum of a body wave has been studied with special emphasis on peaks, troughs and corresponding periods.

Theoretically, the possible causes by which the peaks and troughs can be generated in a spectrum of a body wave are as follows:

1. The Source Mechanism at the Origin.

a. According to the distribution of an initial stress at origin, peak(s) and trough(s) may be generated in the spectrum of a radiated body wave. For the excitation caused by a double-couple type of stress distribution, the trough period in the spectrum (T_t) (the period corresponding to the minimum amplitude) is approximately given by:

$$T_t = \text{radius of spherical origin/shear wave velocity} \quad (1)$$

for the P wave. The spectra generated by various other distributions of stress are also being investigated.

b. The hypothesis of a moving source introduces a series of peaks and troughs in a spectrum of a body wave.

The periods of the troughs are functions of the azimuthal angle θ_0 and the rupture velocity v , and are given by

$$T_t = \frac{1}{N} \frac{b}{C_r} \left(\frac{C_r}{v} - \cos \theta_0 \right) \quad (2)$$

where b is the extension of the fault and N is an integer.

2. Selective Reflection and Refraction at Multilayered Discontinuities

If there is a multilayered medium, selective reflection and refraction occur as a result of interference. The reflection coefficient has been computed for a free surface.

The computed reflection coefficient shows a series of minima in the amplitude. The corresponding periods are functions of the incident angle, the elastic contents, the densities of the layers and the thickness of the layers.

3. The Effect of a Time Window

For a given time function $f(t)$, the effect of a time window used in a spectral analysis can be expressed by

$$\bar{m}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \bar{m}_1(\omega \cdot t) \bar{m}_2(t) dt \quad (3)$$

where

$\bar{m}(\omega)$ is a computed spectrum

$\bar{m}_1(\omega)$ is a Fourier transform of $f(t)$

$\bar{m}_2(\omega)$ represents the effect of a time window.

If the time window $g(t)$ is given by

$$\begin{aligned} g(t) &= 1 & T_1 \leq t \leq T_2 \\ &= 0 & t < T_1 \text{ or } t > T_2 \end{aligned} \quad (4)$$

$\bar{m}_2(\omega)$ is expressed by

$$\bar{m}_2(\omega) = \frac{2}{\omega} \sin \frac{\omega}{2} (T_2 - T_1) e^{i \frac{\omega}{2} (T_2 + T_1)} \quad (5)$$

Therefore pseudo peaks and troughs of the spectrum may be introduced by this phenomena.

4. The Effect of Superposition of Multiple Arrivals

If the seismogram consists of two (or more) arrivals of succeeding body waves with a time separation τ (such as P and $_pP$, PKP₁ and PKP₂, and S and sS), these waves will interfere and give a resultant amplitude modulated wave train.

The spectrum of this resultant wave train $f(t)$ is given by

$$\bar{m}(\omega) = \int_{-\infty}^{\infty} \left\{ f(t) + a f(t - \tau) \right\} e^{i\omega t} dt \quad (6)$$

where a is a constant ($|a| \leq 1$).

For $a \approx 1$, this can be approximated by

$$\omega(\omega) = \omega_0(\omega) \left[2 \cos(\omega\tau/2) \right] e^{i(\omega\tau/2)}. \quad (7)$$

Therefore $\omega(\omega)$ has minimum amplitudes at

$$\frac{\omega\tau}{2} = \left(\frac{1}{2} + N \right) T_2 \quad (8)$$

where N is an integer.

The initial movements of the Chilean earthquake, May 22, 1960, have been analyzed and compared with the theoretical aspects.

No evidence of a moving source given by (2) was found, but at Rio de Janeiro and at Mt. Tsukuba, it is found that there is a good agreement between observed trough periods and computed trough periods from eq. (8) as follows:

1) At Rio de Janeiro ($\Delta = 30.0^\circ$)

Observed trough periods (sec.)	120.	37.3	22.5	17.3
Computed trough period from eq. (8) for $t = 57.5$ sec.	115.	38.3	23.0	16.5
N	1	2	3	4

From the J. B. Tables, the time interval t between PP and P is given as

$$t = 57.5 \text{ sec.}$$

2) At Mt. Tsukuba ($\Delta = 153.2^\circ$)

Observed trough periods (sec.)	(20.8)	15.9	9.3	7.2
Computed trough period from eq. (8) for $t = 23.3$ sec.	46.6	15.5	9.3	6.1
N	1	2	3	4

From the J. B. Tables, the time interval t between PKP_2 and PKP_1 is given as

$$t = 21.9 \text{ sec.}$$

This implies that the use of the trough periods caused by interference gives a good clue on how to separate multiple arrivals of body waves with a small time interval.

J. Surface Wave Inversion Studies

A paper entitled "Seismic Waves and Earth Structure in the Canadian Shield" by J. Brune and J. Dorman was published in the Bulletin of the Seismological Society of America. For this paper careful measurements of phase velocities in the Canadian shield have been made in the period range 3 to 90 sec for Rayleigh waves and 12 to 60 sec for Love waves by phase correlation of wave trains. The continental Love wave phase velocity data are the first to be reported in the literature. The phase and group velocities are higher than yet found in any other continental area, indicating relatively higher shear velocities in the crust and upper mantle. For paths in the Canadian shield a prominent L_g arrival with a velocity of almost 3.65 km/sec is

observed and an Sn arrival is recorded clearly to distances of about 4000 km with a velocity of about 4.72 km/sec.

A theoretical layered model of the crust and upper mantle consistent with the various types of data has been derived by an inversion method employing least-squares curve-fitting of phase velocity data. This model has a three-layered crust 35.2 km thick with shear velocity increasing to about 3.85 km/sec in the lower crust. The upper mantle has a high speed layer with shear velocity 4.72 km/sec down to about 115 km below which the low velocity channel has a shear velocity of about 4.5 km/sec down to a depth of about 315 km. At greater depths the shear velocity closely follows the Gutenberg model.

Higher mode phase velocity dispersion curves computed from the theoretical model are used for computing theoretical seismograms for the Canadian shield. These theoretical seismograms possess many of the features of the observed Ig arrivals, showing that Ig can be explained by normal mode wave propagation in a simple, layered crust.

This paper shows that new methods of measuring and interpreting surface wave dispersion, combined with travel time data, can provide detailed and reliable information on shear wave velocity distribution down to depths of a few hundred kilometers in regions of horizontally uniform structure.

K. Use of Partial Derivatives of Surface Wave Phase Velocities

By using energy equations, which are equivalent to fundamental equations and boundary conditions in surface wave problems, one can obtain analytical expressions for partial derivatives of phase velocity with

respect to physical parameter changes within the earth. These derivatives can be calculated by knowing only the eigenfunction corresponding to the phase velocity. Numerical examples were worked out for CAPSD proposed by Brune and Dorman for the Canadian shield, the Jeffreys model and the Gutenberg model for crust-mantle structure. The application of these results to numerical inversion of surface wave data has been demonstrated for the Canadian shield.

Item 4 - Development of seismic instrumentation with increased sensitivity in the long period range and with improved discrimination against noise in the dominant microseism band.

A. Seismometers with Displacement Transducers

One method of increasing the sensitivity of seismometers in the long period range is to use displacement transducers instead of velocity transducers. Therefore the Lamont Geological Observatory set itself the task of developing reliable displacement transducers for long period seismographs. This has been accomplished.

The system consists of the following: three-component long period seismometers with a free resonance period of 15 seconds equipped with displacement transducers of the capacitance type and associated amplifiers to give a sensitivity of 25 millivolts per micron ground displacement amplitude. The system provides feedback control circuitry for maintaining center alignment of the long-period seismometers. Gravity and tilt information are provided by monitoring the feedback signal required for servo centering.

The basic seismometers used are modified Press-Ewing type instruments manufactured by the Lehner and Griffith Division of United Electro-Dynamics. The associated electronics have the following specifications:

Output level: + 2.5 volts DC \pm 50 percent with a zero to five (5) volt capability

Output sensitivity:

Seismic output: .25 mv/mu
2.5 mv/mu
25 mv/mu
depending on gain setting

Feedback output: .232 volts/second of arc or 290 volts/cm/sec²

Long-term stability:

Seismic output: 5% of full scale

Tidal output: .5% of full scale

Linearity: 10% of best straight line

Equivalent input noise: 25 μ v p-p for 90% of the time

Frequency response: (Filter Passband)

Seismic path: 1/60 cps to 10 cps

Feedback path: DC to 1/2350 cps

Attenuation factors: 1, 10 and 1000 (nominal)

Briefly, the principle of operation is as follows: The outer plates of the balanced capacitance transducer are excited by an oscillator through a center-tapped transformer, in push-pull fashion.

Relative motion between these and the center plate of the transducer is picked up as an amplitude-modulated, suppressed-carrier voltage, amplified and detected in the Synchronous Demodulator. The output is filtered to suppress high frequency components and then fed through an attenuator to a high-pass ($T_f = 60$ sec) filter to remove the DC component. It is then further amplified by the Seismic Amplifier.

The output of the Demodulator is also applied to a low-pass ($T_f = 2350$ sec) filter whose output is used for continuous servo-centering of the transducer through a coil-magnet assembly. This assembly is also used to provide the proper damping for the seismometer. Resistor R_{fb} determines the amount of this positioning feedback and resistor R_d provides the damping. The feedback signal is proportional to long-period motion of the seismic mass. The other side of the seismometer coil is connected to a 2.5 v supply source, so that the reference level is established at mid-scale.

In-phase and 180-degree out-of-phase components of the feedback signal are fed into a circuit which centers the vertical instrument should the instrument drift outside its operating range. The system is calibrated by applying a current pulse into the seismometer coil through an attenuator working in reverse fashion from the attenuator in the seismic path.

These instruments, with and without twin-T band rejection filters in the seismic output have been in continuous operation at Lamont for several months. Three-component seismic outputs and three-component tidal outputs are recorded routinely.

These instruments demonstrate excellent mechanical and electrical stability and minimize the need for the electromagnetic transducers standard on many seismometers which introduce an inherent 6 db octave drop-off in the response to long period signals. The use of instruments of this type will allow long period seismic signals to be recorded more easily than heretofore. The tidal outputs record solid earth tides routinely and at the same time provide an extreme long period seismic response so that long period mantle surface waves may also be recorded. Although these systems are currently more expensive than standard seismometers, the technique will prove more than worthwhile.

B. Use of Surface Wave Rejection Filters to Record Mantle Waves of Low Order

Following the successful use of galvanometer band-rejection filters to reduce microseismic noise, the same technique is being used to filter ordinary surface waves and thus obtain clear recordings of early mantle wave trains from large earthquakes. The long-period waves are usually so obscured by the ordinary surface waves that it is difficult to analyze them. For several recent large earthquakes, clear records of mantle waves of order R1 (travelling directly from earthquake to station) and order R2 (travelling indirect path) have been recorded. The records are ideal data for the study of source mechanisms of large earthquakes, i.e. the determination of such information as length of fault and orientation of forces.

At present the system consists of a normal 30-100 long period Press-Ewing seismograph system with three band-rejection filter galva-

nometers in series. Each filter galvanometer is preceded by a 3000 Ω shunting resistor. The value of these shunting resistors is critical in determining the shape of the response curve for the system. For larger values of shunting resistance, the system is more tightly coupled with greater sensitivity but a more distorted response curve.

The periods of the filter galvanometers are set at 15, 25 and 35 seconds. The choice of periods is also critical in determining the response of the system. With the present system the filter galvanometers occasionally overload (rebound against the stops) for large earthquakes. It may be necessary to add one additional filter galvanometer to correct this situation. The system as presently operated has been calibrated by analysis of its transient response.

Item 5 - Conduct studies and develop techniques in the use of specialized instrumentation for seismic data recording and analysis. Included would be investigations of tape recording systems, filtering, digital analysis and analogue computers for the purpose of improving detection techniques and methods of analysis of seismic records.

A. Analogue Techniques

Analogue computational techniques may be used in conjunction with present seismic instrumentation to extend their capabilities. Also, only by the use of analogue techniques will it be possible to process the flood of data which will arise in connection with the needs of Project VELA. Several new techniques for analysis of seismic data have been developed. These include the following items:

- 1) For many problems involving successive filtering to look

at different portions of the frequency spectrum, particular slopes on the seismograph response curves are required. In addition, inverse filters are required to shape the instrumental response or to remove the instrumental effect entirely from the seismogram. The building of inverse filter elements is particularly simple using analogue computer components in the design stages. The use of these inverse filtering techniques will become progressively more important as more magnetic tape data become available.

2) Successive filtering of long-period seismic signals has been shown by Sutton and Pomeroy to be highly effective in removing microseismic noise and in the selection of desired portions of the frequency spectrum for subsequent analysis. This technique which enhances the signal to noise ratio allows, in some cases, the identification of waves otherwise obscured by higher amplitude waves of different period. It is important in performing analyses of this type to remove the filter phase shift characteristics from the seismogram. This is done by playing the seismic signal through the filter, recording the filter output and playing the rerecorded signal back through the filter backwards in time. This results in a flat phase spectrum but the amplitude response of the filter as it affects the signals is squared.

3) The output from the inverse filtering arrangement described under 1) can be squared and integrated with optional filtering to provide an output proportional to $\int \dot{u}^2 dt$ which is a measure of the kinetic energy associated with the ground motion at a particular station. The value of this integral can be summed for all three components of ground

motion to give a measure of the total kinetic energy observed. This number, in turn, gives some measure of the source energy but of course does not take into account the variation of body wave energy with angle of incidence (with epicentral distance) or variations in surface wave energy with azimuth. The study of the energy accumulation as a function of time shows wide variation on the three components. The measure of the total energy accumulated if a narrow band filter is used gives a rough measure of the power spectrum of the time series on the magnetic tape.

4) If the time series is multiplied by sine and cosine functions and the separate results are integrated to form the values of $\int f(t) \begin{Bmatrix} \sin \omega t \\ \cos \omega t \end{Bmatrix} dt$, the Fourier sine and cosine coefficients result, which, if squared, added and the square roots taken, give the Fourier amplitude coefficients. These coefficients have been derived for several earthquakes and for the USSR nuclear shot of October 30, 1961. The spectrum of the nuclear explosion as recorded at Palisades and as derived using the above techniques, is remarkably similar to digital spectra of USSR explosions of the 1958 series as recorded at Palisades and derived using digital computers. The exception is that there is evidence of some stronger long-period generation for the 1961 series.

5) If the azimuthal angle of a given seismic event is known, a rotation of axes analysis may be performed using simple analogue components so that fine transverse and longitudinal records may be obtained. Once this analysis has been performed, the longitudinal and vertical components may be multiplied together to separate compressional type particle motion from shear type particle motion in most cases.

Several earthquakes have been identified using this technique and several unusual features have become apparent which were reported by Pomeroy and Sutton at the Seismological Society of America meetings in Los Angeles in April 1962.

B. Relative Excitation of Long and Short Period Waves

A study was made of the relative excitation of long period and short period seismic waves by earthquakes and explosions in the California-Nevada region. The Richter magnitude, M , which is based on the amplitudes of short period waves recorded at sites less than 600 km from the epicenter was used as a measure of short period waves. A new parameter, AR - the sum of the areas of the envelopes of the surface waves on certain three-component long period instruments - was defined and used as a measure of the long period waves. The surface wave parameter was determined from long-period seismograph records from Pasadena, Berkeley, Ruth, Reno and Palisades. The four West Coast stations provided good azimuthal sampling of most of the events studied. Surface waves recorded at Palisades from the Fallon-Stillwater, Fairview Peak-Dixie Valley after shock sequences were also studied.

There is a wide range in the excitation of surface waves for a given Richter magnitude, both for explosions and, especially, for earthquakes. For any given earthquake there may also be a wide range in the excitation of surface waves as a function of azimuth, an indication of an asymmetrical radiation pattern. Generally speaking, the relative excitation of surface waves by explosions is much smaller than by earthquakes of the same Richter magnitude. Most of the earthquakes studied generated surface waves 5 to 10 times greater than the maximum observed for explosions of the same Richter magnitude.

A comparison of the relative excitation of surface waves in different regions indicated a very large regional variation. Shocks off the coast of northern California generate relatively large surface waves whereas shocks near Laguna Salada in Baja, California, often generate very small surface waves.

An empirical curve was derived for the variation of the surface wave parameter AR as a function of distance. It was suggested that the parameter AR may be used to estimate the surface wave magnitude M and a formula is derived for doing this.

The results of this study were submitted to the Journal of Geophysical Research for publication under the title "Relative Excitation of Surface Waves by Earthquakes and Underground Explosions in the California-Nevada Region", by James Brune, Alvaro Espinosa and Jack Oliver.

From the study of the relative excitation of long period surface waves by earthquakes and explosions in the California-Nevada region reported above, it was concluded that, for a given Richter magnitude, contained underground nuclear explosions generate relatively small surface waves compared to earthquakes. It is suggested that it may be possible to use this fact as a criterion or diagnostic aid to identify certain events as earthquakes. It must, of course, always be borne in mind that the results described here are based on a relatively small sample of events from a relatively limited number of regions. There is no guarantee, for example, that a nuclear explosion fired under different circumstances will not generate long period waves even though such a result is not predicted by elementary theory.

As an example of how the above criterion might be used, we have made a statistical study of the number of earthquakes studied which produce a value of AR 1, 2, 5 and 10 times the maximum expected for underground explosions at a corresponding distance and Richter magnitude. For a given natural event and safety factor, e.g. 1, 2, 5 or 10, the criterion is said to fail (i.e. fails to identify the event as a natural event) if no observed value of AR is equal to or greater than the maximum value of AR expected for explosions at that distance and magnitude, multiplied by the appropriate safety factor. Otherwise, it is said to succeed. We have limited the magnitude range to $3.91 \leq M \leq 5.5$. The data for $M < 3.91$ are less reliable because of the spacing of the stations and the microseism noise level. Of the 77 earthquakes studied, 63 recorded a value of AR greater than the maximum expected for explosions.

The smaller the ratio of natural events not excluded to the total number of natural events, the more successful is the method in identifying natural events. Depending on the safety factor and magnitude range chosen, this ratio varies from $41/77 = .53$ for a factor of 10 and magnitude range 3.91 - 5.5 to $1/16 = .06$ for a factor of 5 and magnitude range 4.71 - 5.5.

If the lower California earthquakes are excluded from consideration, in the magnitude range 4.31 - 5.5 the ratio is $0/21 = 0$. for a safety factor of 2, $1/21 = .05$ for a safety factor of 5, and $3/21 = .14$ for a safety factor of 10,

The reason for the great excitation of surface waves from the earthquakes off northern California, and the very low excitation for certain earthquakes in lower California is not known, but could be partly due to different source mechanisms, depth effects, poor magnitude determination or different orientation of the radiation pattern with respect to the long period stations.

Palisades long period records were also studied for earthquakes in this region. Most earthquakes above magnitude 4.5 recorded long period surface waves and fell above a safety factor of 2, and many above a safety factor of 10.

C. Subsurface Recordings of High-Frequency Seismic Waves

1. Instrumentation

In late 1961 a vertical seismometer with electronic amplification was installed at the Lamont Seismograph station located on the 1850-foot level of the New Jersey Zinc Company mine near Ogdensburg, New Jersey. The system employs a Hall-Sears HS-10 transducer with a natural frequency of two cycles/sec, an SIE GTR-200 amplifier system, a high-speed photographic drum recorder, and a two-channel magnetic tape recorder. The original drum recorder operated at 120 mm/min; since April 1963, a Sprengnether auto-recorder has been used with a paper speed of 300 mm/min. In both cases the SIE amplifier drove a 200 cycle/sec "pencil" galvanometer. Magnetic tape recording of the SIE amplifier output was done on a two-channel magnachord recorder, with Mnemotron pulse frequency modulation units used in conjunction to provide a pass band from D.C. to 300 cycles/sec. Recording was done on 1/4" tape, at 7 1/2 in./sec. A ten-inch reel would record two hours of data.

The transducer-amplifier system has been calibrated in three steps. First, a method employing a Willmore bridge yielded the relative response of the transducer-amplifier system. The method takes into account the frequency dependent impedance of the SIE input transformers at frequencies near and below 1 cycle/sec. Second, the electrodynamic constant of the transducer was measured by observing the damping as a function of the resistance terminating the transducer coil winding. Third, the gain of the amplifier, expressed in terms of a galvanometer deflection per input voltage, was measured for each record by means of a test signal from an oscillator within the SIE amplifier system.

The over-all magnification of the system with photographic recording increased at 6 db/octave in the frequency band between about 3 to 100 cycles/sec. The system was usually operated at a magnification of 8 million at 20 cycles/sec. During the quietest recording times, the amplifier noise was a factor of ten lower than the equivalent ground noise over the frequency band used.

2. Data Analysis

The most outstanding characteristic of the seismic motion measured at the mine station is the large amplitude disturbances during daytime and early evening that originate from milling and rock crushing operations associated with the mine and with a limestone quarry nearby. The disturbances from these sources are especially predominant at frequencies above 10 cps. Because of this high daytime noise level, most recording was done in the middle of the night. During such quiet times, approximately 800 hours of photographic recording and about 20 hours

of tape recording were obtained on the 1850-foot level with the geophone-amplifier system. In addition, about 20 hours of both types of recording were obtained during daylight hours.

Investigation has been, so far, focused on the quiet nighttime periods. Studies of the continuous seismic background noise, as well as the various discrete signals of natural and cultural origin, are in varying states of progress. Results from the studies are presented below.

(a) Continuous seismic background noise: Several two-minute samples of the quiet nighttime background noise, recorded on magnetic tape, have been analyzed with one octave band pass filtering. The resulting amplitude per octave spectra show a sharp drop-off in amplitude by a factor of 10 from 0.5 cycles/sec to about 2 cycles/sec. At higher frequencies the amplitude falls off at a rate of about -6 db/octave. The analysis was carried out to about 40 cycles/sec. At higher frequencies the noise level of the system obscures the results.

The University of Michigan recorded and analyzed a sample of ground noise at a surface site very nearly above the 1850-foot level mine site. Their results, after adjustment to differences in the analysis procedure and compared with the 1850-foot level measurements, show that at frequencies less than one cycle/sec the amplitudes on the surface and at depth are comparable, but that at higher frequencies the noise level underground drops off faster, reaching a level one-fifth that of the surface noise at about 20 cycles/sec. The presence or absence of the two to three cycles/sec spectral maximum, observed by

University of Michigan investigators at many surface sites, including Ogdensburg, is being currently examined by means of high resolution analysis.

(b) Teleseismic body phases: The only body phases from distant events (Δ / O°) which have been observed to contain seismic energy above about two cycles/sec originate from West Indies earthquakes. Three such shocks have been photographically recorded during quiet background noise times, and are listed below:

1. April 20, 1962, N. Coast of Haiti
(USCGS O = 05:47:55.3, 20.6N, 72.2W)
2. May 20, 1962, N. of Puerto Rico
(USCGS O = 15:01:20.7, 20.5N, 66.0W)
3. March 13, 1963, Dominican Republic
(USCGS O = 10:39:19.1, 19.5N, 69.5W)

The peculiar high frequency P and S phases often observed at eastern U.S.A. stations from such shocks were well recorded in all of these three cases. In the first two cases, the signals were not well enough resolved on the photographic paper to measure the frequencies in the signal. Frequencies as high as 10 cycles/sec seemed to be present. In the third case an excellent recording was obtained at 300 mm/min. Visual inspection showed significant energy as high as 5 cps following both the P and S phases.

Body phases from other distant earthquakes were observed, but with a frequency content no different than that indicated by recordings on more conventional short period seismographs such as the standard station Benioffs. More detailed work will be done in order

to give an upper limit to the propagated energy with frequencies above 3 cycles/sec for the various larger earthquakes that occurred when the geophone was recording.

At frequencies around one cycle/sec the geophone-amplifier system has no particular advantage over conventional one-second transducer-galvanometer systems. During daylight hours, as discussed above, the noise levels at higher frequencies are high. Consequently, little has been done with regard to detecting nuclear shots from Nevada.

(c) Discrete signals of local or regional origin: During the quiet nighttime periods, several types of signals of known cultural origin are often recorded. Railroad trains running along a track about 4 km distant at the nearest point produce a signal lasting several minutes, which is marked by a very strong three to four cycles/sec component. This dominant frequency is also observed in recordings of trains at a surface site, Sterling Forest, which is about 7 km from the nearest railroad track. This phenomenon is currently under investigation; at present, it is believed that the dominant frequency results from impulses generated by the train wheels traversing the track joints. Quarry blasts are occasionally observed during the earlier parts of the night. Most quarry blasting, however, is done during daylight hours.

Several other types of transient signals have been observed whose origins at present are not definitely known but are suspected to be of an artificial nature. Very short duration high-frequency "blips" occur occasionally, about once a night on the average, and are believed to be due to small local readjustments resulting from the daily mining activities. Irregular, rather nondiscrete disturbances of variable

duration and frequency content also occur and are attributed to rock falls within the mine workings. A peculiar pattern of disturbance, lasting for about two minutes, and repeated almost exactly several times for many nights, is suspected to originate from a rocket testing installation in the vicinity.

Truck traffic on a major highway 2 km distant produced no perceptible signals on the 1850-foot level instrument.

The records have been examined closely for the presence of signals that might indicate the occurrence of small earthquakes in the region. 733 hours of geophone amplifier recordings during times of quiet background noise conditions were searched for signals with the characteristic P-S signature. Fourteen events were found. On the basis of investigations to date, 8 are believed to be small earthquakes. Short period standard station records obtained in the mine, as well as recordings from a portable Benioff at Sterling Forest, New York were also examined for events occurring during the middle of the night; a total of 2000 hours for the two instruments yielded 6 events suspected to be small earthquakes. Richter magnitudes were estimated for these 14 events and locations were determined for those large enough to be recorded at several stations. Distances to the events from Ogdensburg ranged from 10 to 290 km, and magnitudes ranged from -0.3 to +2.5. The located epicenters conform with historical and previous instrumental determinations of areas of seismic activity.

Our data, combined with previously published historical and instrumental data, has been utilized to estimate the seismicity of the region within 300 km of Ogdensburg, New Jersey. If the data is plotted

in terms of a number of events per unit area per unit time with magnitudes equal to or greater than some magnitude (the independent variable), results are obtained consistent with a linear relation between the logarithm of the number so defined and the magnitude. A slope of -0.9, found by other investigators in such areas of high seismic activity as Japan, Southwest Russia and Southern California, seems to fit the data fairly well.

In normalizing the observed number of events to a number per unit area, a correction has been applied, peculiar to each instrument, which takes into account the variable area monitored by a particular instrument for a given magnitude event. The correction comes from an estimated relation between the minimum magnitude event detectable and the epicentral distance. Recorded events judged near the threshold of detectability were used to estimate the relation, for the most part. The geophone-amplifier system, having the greatest magnification in the 5 - 50 cps frequency band, monitors a greater area for a given magnitude event than the conventional Benioff instruments and is exceptionally sensitive to very small and local events. Asada in Japan and Sanford and Holmes in New Mexico, both using instruments similar to the geophone-amplifier system, were able to detect shocks with magnitudes as low as -2. Their results were employed in estimating the minimum detectable magnitude for the geophone-amplifier system at short distances.

The resulting estimate of the frequency distribution of earthquake occurrences with respect to magnitude for the New York region gave 6×10^2 earthquakes per year per 10^5 km with magnitudes equal to or

greater than zero. Similar estimates of the seismicity of two seismically active regions indicate that the New York region is three orders of magnitude less active than the Kanto region of Japan and two orders of magnitude less active than Southern California.

Item 6 - Conduct tests to increase the knowledge of crustal structure by land refraction methods. Field studies, using a portable seismic recording system, will be conducted at selected sites.

Some identifications have been made of the quarries responsible for blasts recorded in connection with the short period studies in a deep mine, previously described in this report, for the purpose of future studies along these lines. Otherwise, very little research of this type has been carried out because it was felt that research in other directions was more suitable for the aims of Project VEIA.

Item 7 - At a site to be designated by the Contracting Officer, establish a long period seismograph station to form, with the existing Palisades and Waynesburg Stations, a tripartite array for basic studies of body and surface waves. An additional station within the large array may be established to form a smaller inner array if these studies indicate it to be advantageous.

No suitable site was found. The additional station within the proposed array was set up at Sterling Forest near Tuxedo Park, New York. Since this item was first proposed, we, as well as others working with data from large arrays, have experienced difficulties because horizontal velocity gradients over the net cause variations from the

expected azimuths of the arrivals. Accordingly, it is likely that any further work with arrays will concentrate on arrays composed of stations short distances apart and located as much as possible within the same geologic province.

Item 8 - Develop techniques for analyzing microseismic data and conduct studies of the microseismic spectra.

A. Direction of Approach of Microseisms

Analogue methods have been used to determine the direction of approach of Rayleigh type microseisms. One-hour samples were taken for this study. The azimuth of approach determined is not influenced appreciably by Love waves and random noise. The calculations have been performed on a TR-10 (EAI) analogue computer. The method was applied to several microseism storms recorded at Palisades. The results are in good agreement with those of earlier studies, but they are far more precise. Differences in the periods of microseisms generated by different sources allow the separation of multiple source problems which could not be handled with more conventional photographic analyses. Analysis time is significantly reduced by playback at high speed.

B. A Worldwide Storm of Microseisms with Periods of About 27 Seconds

On June 6, 1961, between about 1200 GCT and 2000 GCT, a storm of microseisms with periods of about 26 to 27 seconds was detected by long period seismographs at many locations throughout the world. No storm of such widespread proportion had ever before been reported. Even though the sensitivity and the geographical distribution of long period

instrumentation, and consequently the ability to detect such a storm, has improved markedly in recent years, this event was so prominent at some stations that it seemed unlikely that similar events had been very frequent in the recent past. There may, however, have been storms of similar nature but smaller size which have gone unnoticed, for many storms of long period microseisms have been observed at individual stations.

In addition to its widespread distribution, this storm was unusual and outstanding in certain other respects. The periods, 26 to 27 seconds, of the waves were considerably longer than the periods of microseisms normally observed, even on the few seismographs operating with high sensitivity in this period range. On such instruments the background noise usually is made up of waves with periods of about 20 seconds or less. For less specialized long period seismographs, the background noise consists of ordinary microseisms corresponding to the well-known peak of the earth noise spectrum between about 3 and 10 seconds (Brune and Oliver, 1959).

The duration of the storm of June 6, only a few hours at most stations, was much less than the duration of most microseismic storms. Ultra-sensitive instruments at one station show that this storm actually had a considerably longer duration, but the interval when the amplitudes were very large was very brief. During this interval the bandwidth of the frequency spectrum was apparently much narrower than in ordinary storms. Whereas the length of a beat in an ordinary storm is usually 5 to 10 cycles, the beats of the June 6 storm were sometimes as long as 40 or 50 cycles.

The June 6 storm also had the property that the periods of the waves decreased gradually throughout the entire duration. At most stations where the storm was observed only for a few hours, the periods of the waves decreased from about 27 seconds to about 26 seconds. At Palisades, where ultra-sensitive instruments are operated, the storm began slightly earlier with periods of about 28 seconds and continued through the interval of large amplitudes for about 2 days until the periods were less than 20 seconds. The gradual decrease of period with time was quite certain wherever observations were good, but the experimental error in measuring the exact period at any given time and the slow variation of period with time prevented a precise determination of the velocity of propagation of the microseisms between distant stations. However, the arrival times were never inconsistent with propagation between stations as seismic waves.

On the basis of particle motion studies, the seismic waves appeared to be predominantly of the Rayleigh type, although some Love waves might have been present as well. When the waves are of the Rayleigh type, the direction of the approach could be determined, and by combining such results from several stations the source of the seismic waves could be localized. The June 6 storm appeared to have originated in or near the southern or equatorial Atlantic Ocean, possibly in the general vicinity of the Gulf of Guinea.

Note 1. In the performance of the above research, the contractor will continue to operate the widely distributed network of long and intermediate period seismic stations that were initially put

into operation in connection with the International Geophysical Year, with such changes in numbers, location or instrumentation as may be deemed desirable for the performance of the contract.

The long period seismic stations initially put into operation during the IGY were continued in operation. During this period, the stations at Hallett, Antarctica; Perth, Australia; Resolute, North Canadian Islands; and Suva, Fiji were discontinued. New stations were placed in operation at Reno, Nevada; Toolangi, Australia; and College, Alaska. Two sets of instruments will be placed in operation at Wellington, New Zealand. The instruments at Agra, India were moved to Delhi.

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13. ABSTRACT A detailed account of the research accomplished as per the Statement of Work of this contract is given herein. Of particular interest to the needs of Project VELA-UNIFORM are the following: a study of the radiation patterns of surface waves from underground nuclear explosions and small magnitude earthquakes, wherein it was determined that the radiation patterns from explosions in tuff and alluvium, but not in granite, could be interpreted as arising from an explosive force acting as a step function in time; a study of the relative excitation of surface waves by earthquakes and underground explosions, which yielded the result that most but not all of the earthquakes studied generated surface waves 5 to 10 times greater than the maximum observed for explosions of the same Richter magnitude; an almost complete summary of Rayleigh wave phase and group velocities for various regions of the world; a program of epicenter relocation carried out so far for the South Pacific Ocean, the Arctic north of 60°N, the Gulf of Aden, Red Sea and Arabian Sea, the African Rift Zone, and the Central Indian Ocean, which showed that in these places at least large earthquakes are confined to much smaller regions than previously thought; successful utilization of displacement transducers with long period seismometers, thereby improving the long period response of these instruments by removing the 6 db/octave fall-off with increasing period, which is inherent in velocity transducers.			

14. KEY WORDS	LINK A		LINK B		LINK C	
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Seismic Source Characteristics Phase Velocity Maps Long Period Seismographs Fourier Analysis of Seismograms Elastic Wave Calculations on Digital Computers Processing of Seismic Data by Analog Techniques Subsurface Recording of High-frequency Seismic Waves Long Period Microseisms						

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