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SEISMIC STUDIES AND EXPERIMENTAL EVALUATIONS

Final Report

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UNIVERSITY OF MICHIGAN 1817

ACOUSTICS AND SEISMICS LABORATORY
Institute of Science and Technology
THE UNIVERSITY OF MICHIGAN

Prepared for
Air Force Cambridge Research Laboratories
Office of Aerospace Research
U. S. Air Force
Bedford, Massachusetts

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PREFACE

The Acoustics and Seismics Laboratory of The University of Michigan's Institute of Science and Technology has been conducting a program of research in seismic wave propagation studies during the last ten years. These studies include field measurement programs, data analyses, theoretical studies, and the development of instruments needed to implement the field and laboratory requirements.

This research has been sponsored in the past by the U. S. Army Signal Corps, the Office of Naval Research, the Air Force Office of Scientific Research, the Air Force Technical Applications Center, the National Science Foundation, and the Air Force Cambridge Research Laboratories. This report covers a three-year and three-month period of research ending 30 June 1963, sponsored by the Air Force Cambridge Research Laboratories under Contract AF 19(604)-6642.

Portions of the research conducted under this contract are being continued under sponsorship of Air Force Cambridge Research Laboratories, Contract AF 19(638)-200, and Air Force Office of Scientific Research, Contract AF 49(638)-1170. This report was prepared primarily by D. E. Willis, to fulfill the requirements of this contract. Since there were some common objectives with the research conducted under sponsorship of Air Force Contract AF 49(638)-911, which was concluded in November 1962, parts of this report are similar to parts of the final report for that contract entitled, Investigation of Seismic Wave Propagation [1].

ACKNOWLEDGMENTS

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ABSTRACT

An extensive three-year field measurement and data analyses program has been conducted to investigate the frequency and energy spectra, amplitude, and attenuation of seismic signals generated by quarry shots, underwater chemical shots, underground nuclear detonations, and earthquakes. This report summarizes this investigation; a number of technical reports have been prepared which present the data in more detail.

A statistical study of earthquake and nuclear-explosion data revealed that particle-velocity ratios of the maximum shear-surface waves to compressional waves can be used as an aid in distinguishing between these two types of source at distances of less than 1000 km. Differences in amplitude, spectra, and energy content of seismic waves were found that could be attributed to source size, depth of source, time duration of source, geological environment at the source and recording station, and azimuthal effects around the source. Since some of the data overlap and conflict, it is difficult to positively differentiate one effect from another. Further investigations of these effects are needed to delineate the useful applications of frequency and energy data for discrimination purposes.

1
INTRODUCTION

A program of seismic research and experimental investigations was conducted under Contract AF 19(604)-6642. The results are summarized in this report, and abstracts of technical reports prepared under this contract are given in the Appendix. Ten reports dealing with the research conducted under this contract have been written. Five have been published in scientific journals, two are in publication, two that have not been published have been presented at scientific meetings, and one will be published as a University of Michigan Technical Report [1A].

The program included an extensive field measurement effort directed toward obtaining broadband (short-period) magnetic tape recordings of seismic signals generated by earthquakes, underground nuclear detonations, and high-explosive (chemical) shots. These measurements were made to provide as much data as limitations of time, personnel, equipment, and funds would permit on the effects of geological setting at the source and at the seismograph station, the effects of different geological conditions along the transmission path, the effects of source size and depth of burial, and attenuation with distance.

Frequency analyses, energy studies, and amplitude and attenuation measurements were made in the laboratory from these recordings. Particular emphasis was placed on determining the differences in frequency spectra as a function of source. This included investigating amplitude ratios of the various wave types.

When appropriate, tape recordings were obtained from other scientific organizations to augment the data collected during this investigation. Many of the recordings, however, were not broadband. Therefore the higher-frequency data of interest to this investigation were not available, so that field measurements by our own field crews were necessary. Most of those measurements were made under sponsorship of Air Force Contracts AF 49(638)-911 and AF 49(638)-1170.

This project has provided part of the data for Air Force Contract AF 49(638)-1079, dealing with the auditory recognition of seismic signals, and part of the data on Air Force Contract 19(638)-200, dealing with seismic background noise.

2
CONCLUSIONS AND RECOMMENDATIONS

Differences in the amplitude, spectra, and energy content of seismic waves generated by earthquakes or by chemical and nuclear detonations have been determined. These have been found to be due in part to azimuthal asymmetries about the source; to differences in magnitude of the source; and, for explosive detonations, to the depth of burial, tamping, medium, decoupling, and (for quarry shots) the number and length of time delays used.

A statistical analysis of large numbers of earthquakes and underground nuclear recordings disclosed that amplitude characteristics of seismic signals can be used as an aid in distinguishing between these two types of events. By using the maximum amplitude ratio between the predominant peaks of the shear-surface and compressional-wave envelopes, 78% of the earthquakes were observed to have larger ratios than the nuclear shots (with the exception of the GNOME shot). When the amplitude ratio was compared as a function of frequency, 58% to 83% of the earthquakes (depending on epicentral distance) could be distinguished from underground nuclear events. These results were for recordings obtained at distances less than 1000 km. Our data are limited at distances between 400 and 1000 km and at distances less than 100 km. Hence it is recommended that additional measurements be obtained to fill the existing gaps. It should be pointed out that whereas the earthquake data were obtained over wide geographical ranges, the nuclear data are confined to a relatively small area of the western United States.

Decoupling factors for chemical shots fired in spherical cavities were found to range from 22 to 200, according to the diameter of the sphere and the size of the shot. The decoupling factor was also found to vary with the frequency content of the seismic waves.

The few local earthquakes recorded on magnetic tape in the eastern U. S. appear to contain higher-frequency seismic energy than those in the West, especially in California. Research conducted on another Air Force contract disclosed that earthquakes recorded in some foreign countries contained much higher-frequency seismic energy than any observed in the U. S.

An earthquake and an underground nuclear shot, both originating at the Nevada Test Site, were recorded in California at the same station with the same type of equipment. The transmission paths were nearly the same for both events. The nuclear shot had much larger amplitudes, comparatively speaking, for the early compressional wave phases; the earthquake had larger amplitudes for phases after P_g. The nuclear shot also generated slightly higher frequencies. This amplitude and frequency relationship may be significant. Hence, it is recommended that a nuclear shot be fired in an active earthquake region and that the shot be well instrumented to verify these observations. The recording stations should be operated long enough to insure recording an adequate number of earthquakes for comparison with the shot recordings.

Because of the overlap and variation in the frequency spectra of seismic waves generated by different sources under varying conditions, it is difficult at present to establish a clear set of rules to distinguish between sources on the basis of peak frequencies alone. The frequency data may be useful in identifying seismic sources, but all the evidence available would have to be studied carefully. Not all the data collected have been completely analyzed, and there are still gaps in the existing data. Hence, this investigation of the frequency content of seismic waves should be continued. The ratios of the peak frequencies, the width and slope of the spectral curves above background noise, and the amplitude ratios of the P, SV, SH, and surface waves should be investigated further.

3
RESULTS AND DISCUSSIONS

3.1. FIELD MEASUREMENTS

3.1.1. INTRODUCTION. During this project an extensive field measurement program was conducted, in conjunction with field measurement programs sponsored by Contracts NOnr-1224(33), AF 49(638)-911, and AF 49(638)-1170. The transducers used in this program included portable three-component seismometers of the Benioff (1 cps natural frequency), Hall-Sears HS-10 (2 cps natural frequency), and Willmore types. Two models of the latter type were used, one having a natural frequency of 1 cps and the other an adjustable period between 1 and 3 seconds. The outputs of these transducers were amplified by wideband seismic preamplifiers (3 db down points at 0.5 and 800 cps) and then recorded on FM magnetic tape recorders.

Considerable time and money were devoted to this phase of the work in order to obtain data in the quantity and quality needed for statistical analysis of seismic signals generated by earthquakes, underground nuclear shots, and high-explosive shots. There are still gaps in the data, but satisfactory progress toward fulfilling these requirements has been made.

To save time and money, the major field trips were planned, whenever possible, so that several types of measurements could be made on the same trip; for example, the underwater shot program was combined with earthquake recording, and the recording of underground nuclear shots was combined with earthquake recording.

The data collection program is summarized below, in three major categories.

3.1.2. EARTHQUAKES. In June 1961 a field trip was made to the Island of Hawaii, to record earth tremors from the Kilauea volcano. Two recording sites were selected, one 14 km northwest of the Kilauea Crater, on the east side of Mauna Loa, and another 13 km southeast of Kilauea, in the Kau Desert. A total of six days recording time was spent at these two sites. Twenty-seven earthquakes were recorded at the Mauna Loa site, and eleven at the Kau Desert site. Detailed analyses have been made for twenty of these earthquakes.

A field trip was made to Hollister, California, to record aftershocks of the 9 April 1961 earthquake (magnitude 5.5). Stations were operated at 5, 28, and 46 km from the epicenter of the main shock. At least 62 aftershocks were recoded on magnetic tape.

In connection with the Hydra II field trip, a station was set up at Mt. Laguna, California, in August 1961. Three-component recordings on magnetic tape were obtained for 45 earthquakes. Most of these earthquakes fall in three range groups: 20-30 km, 70-90 km, and 120-150 km. Several sonic booms were also recorded at this site.

In July 1960, after the Scooter shot was delayed, a tripartite array was established for the purpose of recording earthquakes. Stations were located at the Nevada Test Site; Kingman, Arizona; and St. George, Utah. In about two weeks, eight earthquakes were recorded on magnetic tape at at least two of the three stations. Several earthquakes were also recorded at the Scooter recording sites.

A field trip was made to northeastern New York State to record aftershocks of the Vermont earthquake of 10 April 1962. Six aftershocks and a distant earthquake were well recorded.

A number of other earthquakes were recorded in central California, Arizona, New Mexico, Nevada, Wyoming, Montana, and North Carolina in connection with other field measurement programs.

3.1.3. HIGH EXPLOSIVE SHOTS

3.1.3.1. Quarry Shots. During this project at least 69 quarry shots fired in Michigan and Minnesota were recorded at distances ranging from 30 to 525 km. Sizes of the shots varied from 1000 to 333,170 pounds of high explosives.

Field trips were also made to southern California, Montana, Pennsylvania, and Iowa to record especially interesting quarry shots. At Alden, Iowa, in the fall of 1960, a series of controlled tests were made under the direction of the U. S. Bureau of Mines to determine the effect of ripple firing. A series of one-, three-, seven-, and fifteen-hole shots was fired, with no delays, 17-msec, and 34-msec delays. A number of these shots were recorded on magnetic tape and have subsequently been analyzed in the laboratory.

A field trip was made to Townsend, Montana, where two high-explosive shots were recorded. The purpose of this trip was to obtain recordings of shots in an area where numerous earthquakes had been recorded previously.

Three recording stations were established along a line at distances of 16, 100, and 285 km to record a 59,250-pound limestone quarry shot fired at Tyrone, Pennsylvania, on 15 March 1961. An 87,000-pound shot from this same quarry was recorded in 1962 at the intermediate depth seismic monitoring station ($\Delta \approx 500$ km) near Dixboro, Michigan. Another shot (61,500 pounds) fired at this quarry was recorded on 6 March 1963. Two stations were set up at 50 km from each end of the line-of-shot holes to determine how the direction of shot detonation affected the seismic waves recorded at that distance. A zero-time recording station was also operated for this shot.

In connection with other field trips, quarry and mine shots have been recorded in central and southern California, Arizona, Utah, Nevada, Kentucky, Ohio, and New York.

3.1.3.2. Underwater Shots. In June 1961 a field trip was made to Rockland, Maine, to record a series of underwater shots fired off the coast of Maine. Recordings were obtained of 23 shots, varying in size from 1000 to 3000 pounds of Nitramon, which were fired at given intervals along a line 125 to 340 km from the recording stations.

Another field trip was made to California in July and August 1961 to record a series of 10,000-pound underwater shots. This series, designated Hydra IIα, was conducted by the U. S. Navy. Very good recordings were obtained at distances of 123, 180, and 196 km. Several recordings were also made at the Nevada Test Site at distances of 500 and 518 km.

In July 1962 a series of offshore North Carolina underwater shots were recorded by two University of Michigan field crews. These shots were fired on the bottom of the ocean floor off the coast of Jacksonville, North Carolina, at given intervals out to several hundred kilometers. We operated one fixed station 100 km inland and one portable station at distances of 20, 60, 150, and 190 km.

During August 1962 the University of Wisconsin fired a series of shots in the Mississippi River for the purpose of making crustal measurements. Since seismic waves generated by different underwater shots are almost identical, this series of shots provided an excellent opportunity to make attenuation and azimuthal studies with a limited number of crews.

Recording stations were set up at intervals of 100, 150, 200, and 250 km along lines southeast, east, northeast, and northwest of the shot point, Cape Girardeau, Missouri. Two other stations were located at 100 km north and west, respectively, of the shot point.

3.1.3.3. Other High-Explosive Shots. A field trip was made to Alberta, Canada, to record the 100-ton air shot fired at the Suffield Experimental Station in August 1961. A station was set up 100 km southeast of the shot point. Three-component Benioff siesmometers were used as sensors; the shot was recorded on magnetic tape.

Two major field trips were made in July and October 1960 to record the Scooter high-explosive shot (500 tons) fired at the Nevada Test Site. The shot was recorded at distances of 200 and 300 km along a line east from the shot point (St. George, Utah, and Kanab, Arizona) and along a line northwest from the shot point (Mina and Fletcher, Nevada). In September 1960 one of the Buckboard shots (20 tons) was recorded at the St. George and Kanab sites.

3.1.4. UNDERGROUND NUCLEAR DETONATIONS. During this project eleven major field trips were made in order to record particularly interesting underground nuclear detonations. From one to six stations were operated for a specific shot. Shots were chosen according to size, medium in which they were detonated, and depth. Stations were located to evaluate the above parameters, to measure attenuation, and to allow comparisons with recordings made of high-explosive shots fired at the Nevada Test Site. One station was operated at Hollister, California, to obtain recordings to compare with an earthquake originating within the Nevada Test Site that was recorded at Hollister in January 1959.

Information on the shots recorded by The University of Michigan field crews is summarized in Table I.

3.2. DATA ANALYSES

3.2.1. INTRODUCTION. Most of the data collected under sponsorship of this contract were analyzed by playing the magnetic tape recordings back through 1/3-octave filters and recording on a photographic oscillograph. Particle velocities and energies were computed from these seismograms. Various passband filter settings were also used in the travel-time studies to enhance the signal-to-noise ratio for the initial arrivals. Analog computer, digital computer, and optical analyzer techniques were also used in computing the power spectra of the seismic signals recorded on magnetic tape. Crude frequency analyses were also made with seismic level recorders of the type discussed in Section 3.3.

Spectral analyses of the same recordings have been made by the techniques described above. The results agreed quite closely. The 1/3-octave spectral data have been corrected for instrumentation response and normalized to a 1-cps bandwidth.

3.2.2. PARTICLE VELOCITY COMPUTATIONS

3.2.2.1. Earthquakes. Particle velocities have been computed for the predominant compressional, shear, and surface wave phases for about 260 earthquakes, most of which were recorded in central and southern California, Montana, and the Hawaiian Islands. Analyses have been made for the vertical component on all these recordings, and for the two horizontal components whenever they were available.

The Hawaiian earthquake data were obtained at relatively short ranges, from 1 to 60 km. The epicenters for these earthquakes were on the Kau Desert near one of the recording sites. Particle-velocity computations have been made for the following: recordings of 6 earthquakes made with the vertical component at the Kau Desert recording site; and recordings of 8

TABLE I. UNDERGROUND NUCLEAR SHOTS

Station	Distance (km)	Number of Shots Recorded
Corn Creek, Nev.	95	1
Hope, N. M.*	95	1
St. George, Utah	187	4
Radio Crystal, Nev.	189	2
Cloudcroft, N. M.*	209	1
Climax Claims, Ariz.	212-226	11
Quarter Master View Pt., Ariz.	235	1
Willow Springs, Ariz.	271	1
Kingman, Ariz.	285	2
Truth or Consequences, N. M.*	296	1
Pica, Arizona	322	1
Ramona, Calif.	425	2
Hollister, Calif.	434-461	3
Red Hill, Ariz.*	507	1
Winslow, Ariz.	562	2
Red Hill, Ariz.	740	1
Rifle, Colo.	790	3
Magdalena, N. M.	834-846	4
Truth or Consequences, N. M.	939-944	4
Idaho Springs, Colo.	1000	2
Cloudcroft, N. M.	1044-1056	4
Bonneville, Wyo.	1050±	2
Speed, Kansas	1450±	2
Blue Hill, Neb.	1580	2
Fort Madison, Iowa	2175	2
Grand Marais, Minn.	2500±	1
Peach Mt. Observatory, Mich.	2797	4
Fiborn/Hendricks Quarry, Mich.	2741	2-4
Oneida, Kentucky	2870	2
Beverly, Ohio	3004	2
Washington, Georgia	3051	1

*GNOME shot detonated at Carlsbad, New Mexico.

earthquakes made with the vertical component; and 6 made with both vertical and horizontal componenets, at the Mauna Loa recording site. The predominant frequencies ranged from 2 to 16 cps for the compressional and shear waves; 80% of the recordings had predominant frequencies between 8 to 16 cps. For 90% of the earthquakes, the shear waves were composed of the same frequencies as the compressional waves, or higher. The shear waves (vertical component) also had larger particle-velocity amplitudes than the compressional waves (a factor of 2.6 on the average higher). The horizontal component recordings had slightly larger shear vs. compressional wave amplitude ratios (3.1).

Typical particle-velocity curves for the Kau Desert and Mauna Loa recordings are given in Reference 2. Table II summarizes the Hawaiian earthquake data.

An analysis of the Montana earthquake recordings disclosed a relationship between frequency content and earthquake magnitude. At distances of 110, 150, and 220 km, larger magnitude earthquakes consistently contained lower-frequency energy than smaller magnitude earthquakes recorded at the same distance. These data are described in detail in Reference 3. The Montana data also show a slightly higher frequency content than earthquakes recorded in California, especially in shear and compressional waves. This is shown in Tables III and IV.

TABLE II. HAWAIIAN EARTHQUAKES

Number of Recordings	Epicentral Distance (km)	Peak Frequency (cps)	
		P	S
8	less than 15 km	10 to 16	12.5 to 16
6	20 to 30	6.3 to 16	4 to 16
6	30 to 60	8 to 16	8 to 12.5

TABLE III. CALIFORNIA EARTHQUAKES

Epicentral Distance (km)	Variation in Magnitude	Peak Frequency (cps)		
		P	S	L_R
3 to 20	-0.7 to 1.5	10 to 32	6 to 16	4 to 5
25 to 145	0.2 to 3.0	2.5 to 12.5	2.5 to 6	2.5 to 3.2
155 to 432	1.6 to 4.1	1 to 4	1 to 2.5	0.8 to 2

TABLE IV. MONTANA EARTHQUAKES

Epicentral Distance (km)	Variation in Magnitude	Peak Frequency (cps)		
		P	S	L_R
70 to 150	0.5 to 2.6	2.5 to 10	1 to 10	1 to 10
155 to 250	1.4 to 3.3	0.8 to 4	0.8 to 6	0.8 to 5

A local earthquake recorded at the 123-km and 180-km Hydra II recording system contained the same frequency content for the compressional waves as the underwater shots. However, the shear and surface waves of the earthquake were composed of lower frequencies than those generated by the underwater shots.

Earthquakes recorded in the New England area appear to be composed of higher-frequency seismic energy than western earthquakes, especially those recorded in California.

Copies of the main Vermont shock of 10 April 1962 and its aftershocks have been obtained from three of AFTAC's 40 mobile field seismograph stations, as well as from the regular observatory stations in the New England area. These recordings are being analyzed. The results will be included in a report dealing with this particular series of earthquakes. The current status of the frequency analysis for each of these earthquakes is shown in Table V.

TABLE V. NEW ENGLAND EARTHQUAKES

Epicentral Distance (km)	Peak Frequency		
	P	S	L_R
15*	8 to 45	25	12.5 to 40
150	1.6 to 10	1.25 to 20	1.6 to 12.5
170 to 180	1 to 12.5	1.6 to 8	1.6 to 6.3 and 12.5 to 16
300 to 360	1 to 12.5	2.5 to 6.3	1.6 to 40

*This event was probably a local mine or quarry shot.

An investigation is currently in progress for the analysis of earthquakes recorded in Puerto Rico, Chile, Pakistan, American Samoa, and Greece. Most of these analyses are sponsored by another Air Force contract, but they are of direct interest to this project. The results to date indicate that earthquakes in Chile and Pakistan contain much higher-frequency energy than U. S. earthquakes at comparable epicentral distances.

3.2.2.2. High-Explosive Detonations. Particle-velocity computations have been completed for the underwater shots fired off the coast of Maine and for the Hydra II series. These data are reported in References 4 and 5. To summarize briefly, the 10,000-pound Hydra II shots were found to be effectively tamped at a depth of 60 to 70 feet. The change in shot depth produced no significant difference in the frequency content of the compressional or shear waves. The only measurable difference was observed in the amplitude of the seismic signals. The maximum displacement for tamped underwater shots showed an increase by a factor of 20 over shots fired underground. Charges fired on the bottom were usually found to produce shear waves having larger amplitude than compressional waves. The Maine data showed abnormal absorption factors for compressional waves. The predominant frequencies of the compressional and shear waves were observed to change significantly over relatively small increases of distance between the shot point and the recording station. The latter were kept fixed. The data from the offshore North Carolina and the Cape Girardeau events have not been analyzed yet.

Particle-velocity computations for the 500-ton Scooter shot showed an azimuthal asymmetry in frequency content of the compressional waves generated by this shot [6]. The frequency spectra peaked at 2 1/2 to 3 cps for the stations 200 and 300 km east of the Nevada Test Site. Stations 200 and 300 km northwest of the shot point had predominant frequencies of 1 cps. The same frequencies were observed at the eastern stations for several of the Buckboard shots (20 tons). A mathematical model offering a plausible explanation for this observed asymmetry has been developed [7].

The Pennsylvania quarry shot (59,250 pounds), recorded at 100 km, showed compressional, shear, and surface waves peaking at 3.2, 6.3, and 0.8 to 6.3 cps respectively. The St. Lawrence Seaway shot (60,000 pounds), recorded in New York at the same distance, contained significantly higher frequencies: 9.5, 6.2, and 1.5 to 19 cps respectively for compressional, shear, and surface waves. The Michigan Basin quarry shots, as shown in Table VI, contain predominant frequencies ranging from 0.6 to 12.5 cps.

TABLE VI. MICHIGAN BASIN QUARRY SHOTS

Number of Recordings	Distance (km)	Shot Size (lb)	Peak Frequency (cps)		
			P	S	L_R
6	70 to 86	26,000 to 35,000	2 to 12.5	1 to 3.2	0.8 to 1
6	95 to 107	9,350 to 15,950	1 to 10	1 to 5	0.6 to 1.2
21	142 to 156	4,500 to 19,200	1.6 to 10	0.8 to 4	0.6 to 3.2
8	170 to 183	4,760 to 15,694	2 to 8	2 to 3.2	0.5 to 2.5
6	193 to 218	10,000 to 14,000	1 to 5	2 to 5	0.2 to 3.2

It has been shown that the amplitude and frequency content of the seismic signals generated by the quarry shots depend on the method of firing (instantaneous vs. delayed), depth of burial, and probably the type of rock in which the shots are fired [8, 9, 10]. The amplitudes of the seismic waves generated by ripple-fired quarry shots were found to be a function of the frequency spectrum and to vary differently for the different types of waves. Compressional and shear wave amplitudes were found to be reduced by ripple firing; surface wave amplitudes were found to increase as the 0.70 power of the total charge size. It was demonstrated that the Fourier theory shows that there is a relationship between the spectrum of a signal F(t) and the spectrum obtained by repeating a summation of F(t) a given number of times with a fixed time delay between each repetition. This technique can thus be used to predict the amplitude and spectrum for any size ripple-fired quarry shot where the charge per hole is kept constant and a simple firing pattern is used.

The 100-ton air shot at the Canadian Suffield Experimental Station was recorded at a distance of 100 km. A signal traveling with a velocity of 0.3 km/sec was recorded at this station at a level equivalent to the magnitude of the seismic body and surface waves. Spectral analysis of this "air coupled" wave indicates that the spectrum is nearly flat between 1 and 5 cps, whereas the longitudinal wave spectrum is nearly flat between 1.5 and 16 cps.

Except for difference in amplitude, there is considerable similarity between the spectrum of the "air coupled" wave and the spectrum of seismic background noise as recorded at the time of the explosion.

3.2.2.3. Underground Nuclear Detonations. Particle-velocity computations have been completed for nearly all of the recordings listed in Table I. References 3, 11, 12, and 13 present some of the results of these computations. Several more reports will be prepared upon the completion of the data analysis program now in progress.

This discussion will be limited to data already reported, since some of the remaining data may be classified.

The spectral differences observed between underground nuclear shots and their "aftershocks" were studied. The latter occur when the spherical cavities caused by a shot fired in alluvium collapse under the weight of the overlying material. We have recorded these collapse events as far as Bonneville, Wyoming, a distance of approximately 1000 km from the NTS. In general, the shots were observed to generate higher-frequency seismic signals than the collapse. The firing of shots in different media such as salt, granite, and tuff was found to affect the frequency content and amplitude of the seismic waves generated by these shots.

Although most of our GNOME recordings were overrecorded, an analysis of the first several cycles of P_n showed that the frequency content changed as a function of time. Also, the first half period of P_n increased from 0.14 to 0.20 seconds at distances of 200 and 500 km. Detailed frequency analysis of the recording made at a distance of 95 km disclosed that this shot contained considerably more energy in the region from 5 to 15 cps than the LOGAN shot, fired in tuff, or other nuclear shots, fired in alluvium. This GNOME recording also contained larger amplitude low-frequency (1 cps) surface waves than have been observed from other nuclear shots recorded at comparable distances.

An earthquake of magnitude 4.0 was recorded at Hollister, California, by a University of Michigan field crew on 28 January 1959. The epicenter of this earthquake was located within the Nevada Test Site area (Δ = 432 km). Hence, several of the underground nuclear shots were recorded at this same recording station with the same kind of equipment. A frequency analysis of the two types of event showed that the nuclear shot contained slightly higher frequencies, especially for the shear and surface waves. A rather striking difference in amplitude between the two events was also observed. The early compressional phases of the shot have much larger amplitudes, whereas for the earthquake the phases after P_g are much larger. It would be very desirable to detonate a nuclear shot in an active earthquake area to see whether these observations could be used as a diagnostic aid for distinguishing the two types of events.

Frequency analyses of the LOGAN and BLANCA shots recorded at distances of 786, 1583, and 2175 km show no striking difference in frequency content of P_n at these distances. At 786 km, P_n has peaks at 0.8 cps and 2.5 cps. At 1583 km, P_n peaks at 0.63 cps, and at 2175 km the signal is rather broad, peaking from 0.63 to 0.8 cps. Also, though the maximum amplitude occurs between 0.63 and 0.8 cps, the maximum signal-to-noise ratio occurs at higher frequencies.

3.2.2.4. Seismic Background Noise. It has been the practice in our field measurement program over the past several years to make seismic background recordings in all the different geological environments where our field crews were operating. A sufficient number of these recordings were made, and a frequency analysis of the background noise was performed for each site. The results showed that the only prominent difference among the microseismic spectra is the level of the noise. In general it was found that at frequencies above 2 or 3 cps the noise decreases as the square of increasing frequency. At frequencies below 1 cps the noise was found to vary as the approximate fourth power of the period. A small anomalous effect was noted for most sites at frequencies near 2 or 3 cps. These results are described in detail in Reference 14. Further investigation in seismic background noise studies are currently being sponsored by Air Force Contract AF 19(638)-200.

3.2.3. ENERGY COMPUTATIONS

3.2.3.1. Seismic Energy From Ripple-Fired Explosions. Detailed energy computations were made for 8 quarry shots. Four shots were recorded in Michigan, at a distance of 156 km, and 4 in Iowa, at 0.3 km. Estimates of the energy in seismograms of the compressional and shear waves indicate that the shear/compressional energy spectra ordinarily undergo some variations in ripple blasting; this suggests that part of the observed spectral effects in explosion-generated seismic waves may be attributed to source mechanism. Absolute energy estimates suggest that small explosions are more efficient generators of seismic energy, and that from 0.003 to 2% of the available energy went into seismic waves for the events studied. These data are discussed in more detail in Reference 15.

3.2.3.2. Energy Relationship of Coupled and Decoupled Shots. Energy computations were made for a series of shots fired by the Atomic Energy Commission in Winnfield, Louisiana (Project COWBOY), to test theories on seismic decoupling. Shots ranging in size from 200 to 2000 pounds were recorded at various distances between 1.1 and 14.7 km. Decoupled shots were fired in the center of 12- and 30-foot spherical cavities.

Energy flux spectrum levels for 1/3-octave seismograms were computed for all of these shots. The ratios of the coupled shots to the decoupled ones recorded at the same distance were plotted as a function of frequency. A maximum decoupling factor of approximately 200 was observed for the 30-foot-sphere shots. Reducing the sphere size to 12 feet reduced the decoupling factor to approximately 22. The magnitude of the decoupling was found to depend on the frequency content of the seismic waves.

These results are discussed in more detail in Reference 16.

3.2.3.3. Energy in Seismic Waves Generated by Weight Drops. Energy calculations were made from a series of seismograms obtained at short ranges. Thousand-pound weight drops were used as sources for the sake of simplicity. The results showed a much higher energy content at the origin than theory would predict. The only way to make the observed data agree, within reason, with theory was to assume that spreading was cylindrical and that all the energy was trapped in a relatively thin layer above the water table.

3.2.4. ATTENUATION MEASUREMENTS AND AMPLITUDE STUDIES. Attenuation measurements are reported on in References 3, 4, 10, 11, and 16. Azimuthal asymmetry in amplitude is discussed in References 6 and 7. A statistical analysis was made of the amplitude ratios of shear/surface waves vs. compressional waves for a large number of earthquakes, underground nuclear detonations, quarry shots, and underwater shots recorded over a wide geographic range. The results of this study are summarized in Figures 1 through 4. Figure 2 shows the usefulness of this technique as an aid in distinguishing earthquakes from underground nuclear shots. By comparing the amplitude ratio as a function of frequency, 58% to 83% of the earthquakes, depending on epicentral distance, could be distinguished from underground nuclear events. These results are discussed in more detail in Reference 12. Figures 3 and 4 contain similar data for quarry shots and underwater high-explosive detonations.

3.2.5. TRAVEL-TIME DATA. The travel-time data for the underground nuclear tests recorded by The University of Michigan are reported in Reference 11. The shots fired at the Nevada Test Site show a reasonably good fit to the following equation:

$$P_n - 0 = 7.31 + \Delta/8.0$$

The maximum observed variation from this curve is 0.8 second. Using a P_n velocity of 7.96 km/sec would give a better fit to the observed data.

Most of these data were obtained along a line to the southeast of the Nevada Test Site, toward Carlsbad, N. M., the site of the GNOME shot. The travel times along a reversed profile from GNOME fit the equation

$$P_n - 0 = 7.28 + \Delta/7.8$$

The difference between the P_n veolocities for the GNOME and Nevada Test Site shots could be explained by a small dip of the Mohorovicic discontinuity of about 1/2 degree to the west.

Travel-time data from our recordings of the offshore Maine and North Carolina underwater shots will be included in reports prepared by The Carnegie Institution and the University of Wisconsin.

The MISSISSIPPI underground nuclear shot was recorded at six stations by University of Michigan teams to determine whether there was any azimuthal difference that could be detected at third zone distances. These stations were located at distances ranging from 2741 to 3051 km in Michigan, Ohio, Kentucky, and Georgia. The difference in azimuth from NTS to the stations farthest north and south was about 30 degrees. The maximum observed amplitude of P_n was found to decrease toward the south. A rather large discrepancy in travel time was observed for the Georgia recording. The arrival time of P_n at the other recording sites was about 0.6 to 1.0 seconds earlier than predicted from the Jeffreys-Bullen travel-time curves. However, at the Georgia site P_n was nearly 3 seconds late and was of considerably lower

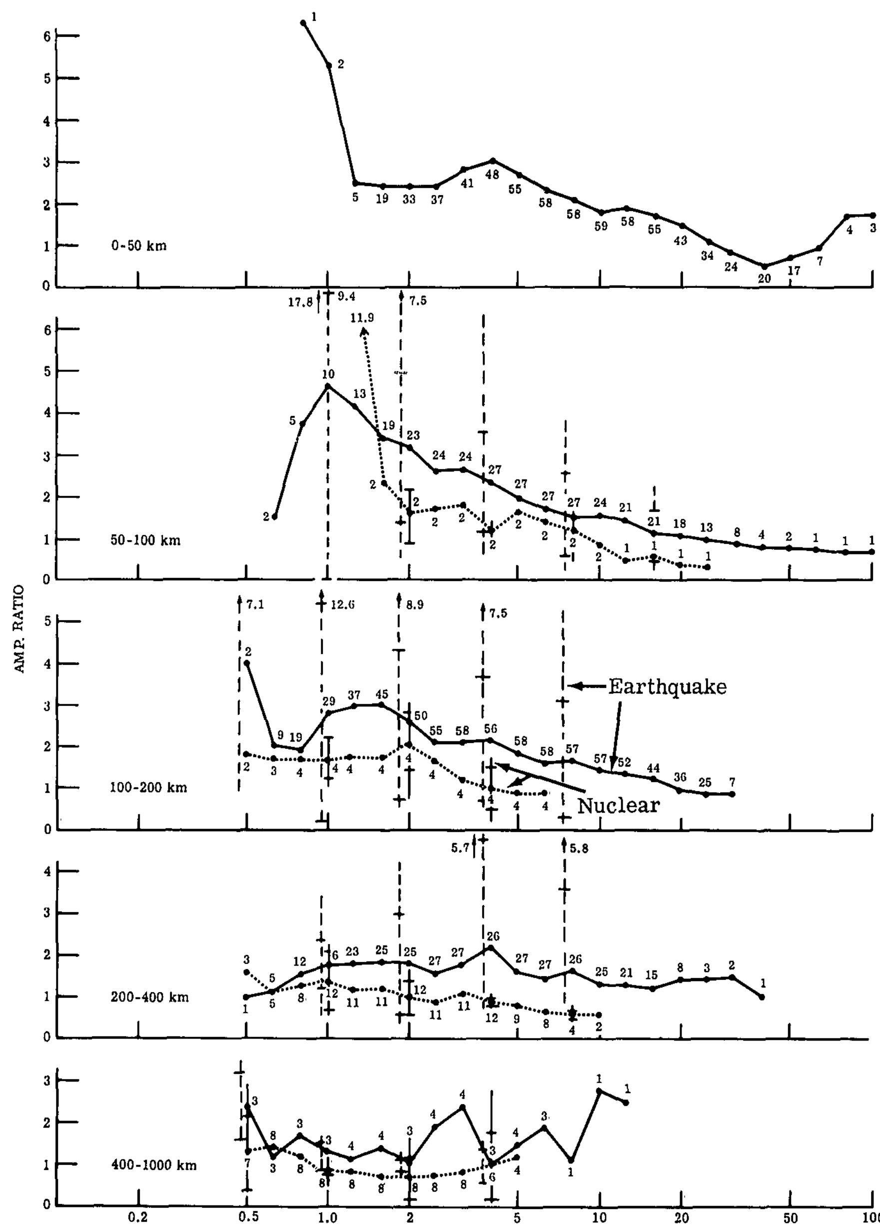

FIGURE 1. AMPLITUDE RATIOS OF SHEAR/SURFACE WAVES VS. COMPRESSIONAL WAVES FOR EARTHQUAKES AND UNDERGROUND NUCLEAR SHOTS AT RANGES BETWEEN 0 AND 1000 KM

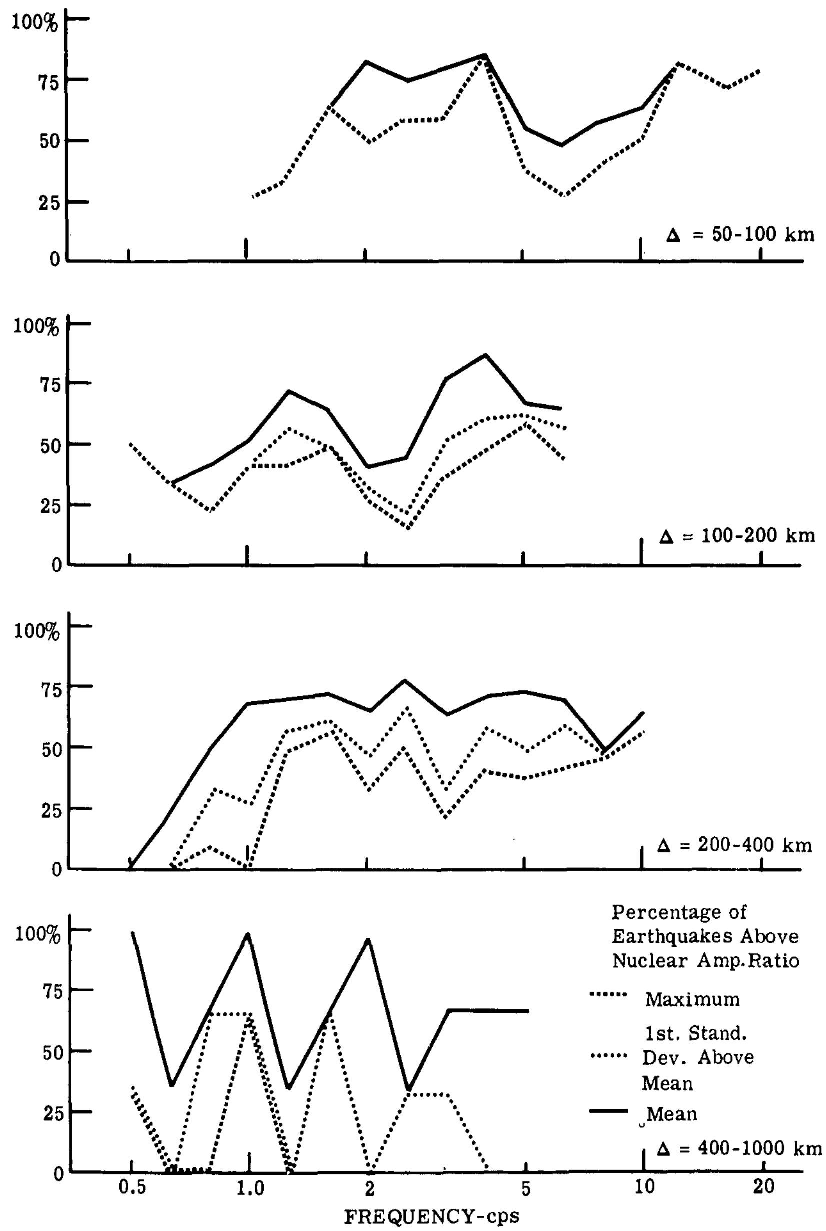

FIGURE 2. COMPARISON OF AMPLITUDE RATIOS OF EARTHQUAKES AND NUCLEAR EXPLOSIONS

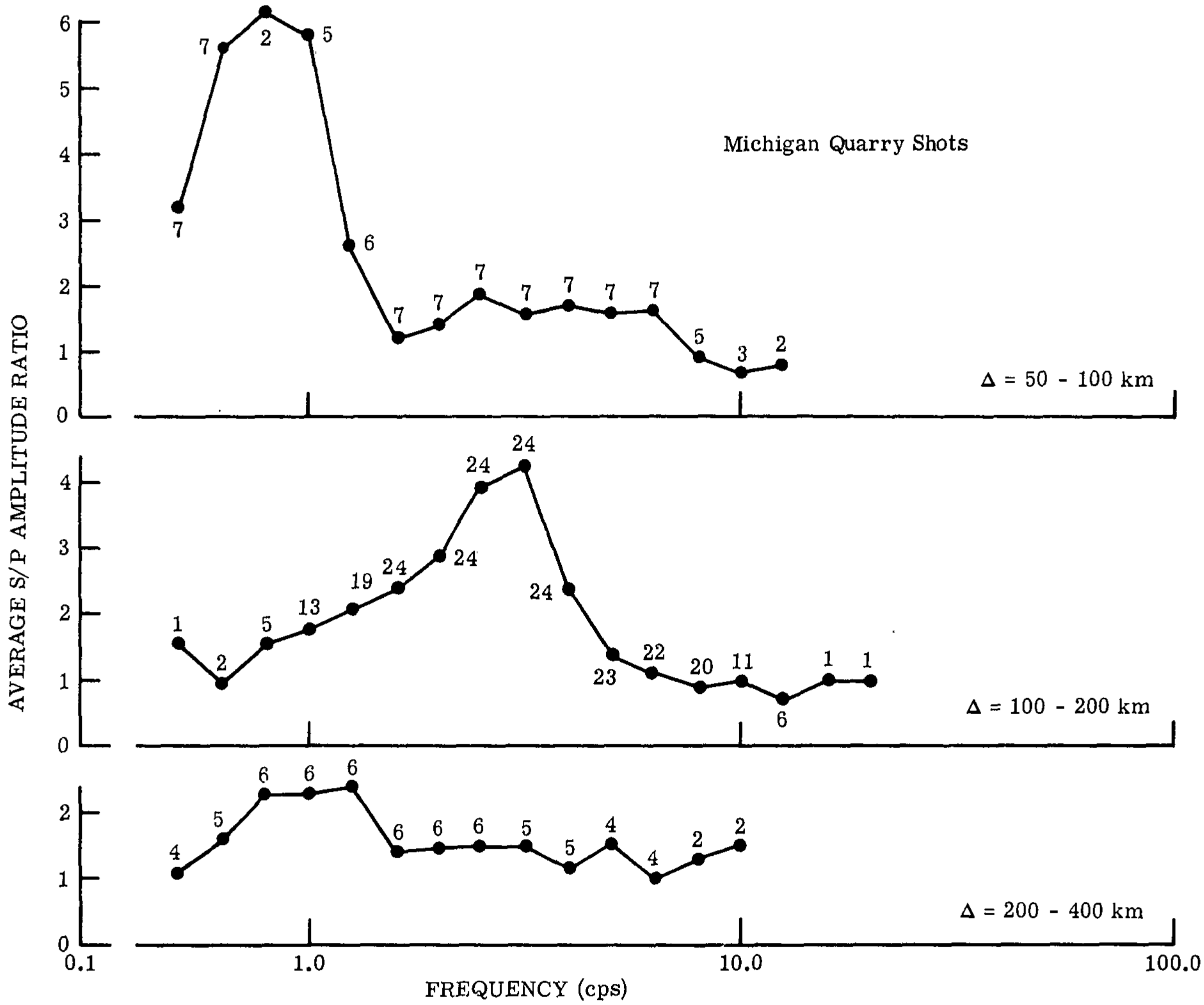

FIGURE 3. AMPLITUDE RATIOS OF SHEAR/SURFACE WAVES VS. COMPRESSIONAL WAVES FOR QUARRY SHOTS RECORDED IN THE MICHIGAN BASIN

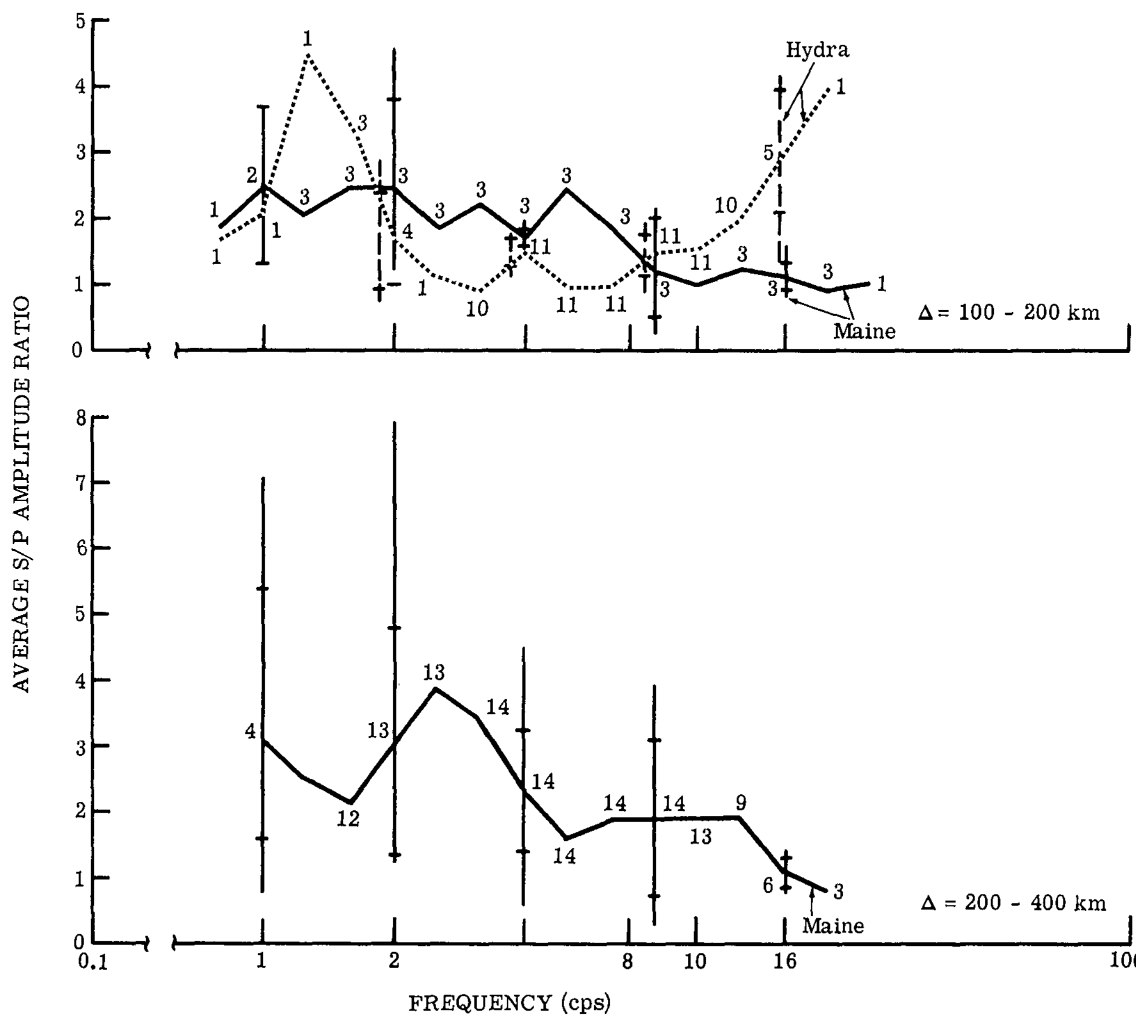

FIGURE 4. AMPLITUDE RATIOS OF SHEAR/SURFACE WAVES VS. COMPRESSIONAL WAVES FOR UNDERWATER SHOTS

amplitude. The results of these recordings will be discussed in more detail in a report that is currently being prepared.

3.2.6. THEORETICAL STUDIES. The observed asymmetry of amplitude from the Scooter shot [6] prompted an investigation into the possible causes for such phenomenon. This investigation was reported in Reference 7, which concluded that the geometry of a point source in a cylindrical low-velocity medium in the vicinity of an otherwise symmetrical source could produce a frequency dependent variation of amplitude with azimuth.

Theoretical investigations were then expanded to include other problems dealing with the radiation pattern of elastic and acoustic waves propagating from cylindrical media about a point source. The first problem concerned a point source on the axis of an elastic circular cylinder that is completely surrounded by an infinte elastic medium of differing properties. The second and third problems are acoustic or fluid problems. A free surface was introduced in both cases. The half-cylinder problem considers a free surface containing the axis of the cylinder with the source below the axis. The truncated cylinder problem treats the case of the axis normal to the free surface. Formal solutions were derived for each case, but no numerical examples were computed. These investigations are presented in Reference 1.

3.3. INSTRUMENTATION DESIGN AND DEVELOPMENT

An instrument was designed and constructed for use as a visible writing recorder to supplement magnetic tape recorders. This instrument, called a seismic level recorder, can be used in the field or in the laboratory to monitor seismic activity. The signal from the seismometer is rectified and filtered so that the d-c output from the recorder is equal to the peak-to-peak measurement of the a-c waveform. A detailed description and some useful applications of the seismic level recorder are given in Reference 17.

To increase our field recording capabilities, top plates for Ampex 352 and 601-2 tape recorders were purchased early in this project. The electronic components necessary for the operation of a complete 7-track and 2-track tape recorder were designed and built, and the two recorders were modified for FM/AM operation.

A completely transistorized polyfilter was designed, constructed, and put into operation to speed up data processing. The polyfilter covers 1/3-octave bands from 0.5 to 100 cps. The filters have zero loss at the center frequencies and have a roll-off of 90 db per octave on either side of the center frequency. They can be used in the field or the laboratory. Since they are accurately preset with a signal generator, the results obtained are much more accurate (and time saving) than those obtained by manually adjusting variable passband filters.

To test the feasibility of a continuous real-time frequency analysis of seismic signals, a mechanical commutator was designed that would allow sweeping the output of the polyfilter. The results were very satisfactory. Hence a commutator using electronic switching is to be constructed to perform this operation.

A new seismic amplifier was designed, and a breadboard model using transistors and nuvistors was constructed, partly on funds from this contract. The principal advantage of the amplifier is its low noise characteristics (0.5 μv from 0.1 to 200 cps), wide frequency response (1.0 to 1000 cps), and low power consumption. Also, it obviates the need for the 90 and 180-volt power supplies, and the 12-volt power drain is considerably reduced. We hope eventually to replace all of our present amplifiers with ones of this general design.

A transient function generator was designed to provide a means of calibrating our filters and other electronic instruments. The generator will provide 16 cycles on and 16 cycles off for any desired frequency up to 1000 cps. The signal starts and ends precisely at the zero crossing, thus providing a means to check the phase response, rise time, and "ringing" characteristics of the electronic equipment being tested.

A portable signal generator was also constructed that makes it possible to calibrate equipment in the field. Our shake table, constructed on an earlier contract, was also modified to calibrate horizontal seismometers. The table has a constant-velocity drive over a frequency range from 0.5 to 100 cps and can be used to calibrate seismometers as large as the portable Benioff.

3.4. FISCAL INFORMATION

It is estimated that the $91,350 allocated for this contract will be expended as of 30 June 1963. The following is a list of capital equipment and components purchased on this contract:

Seismometers	
1 Willmore Mark I	$ 425
1 Willmore Mark II	1056
2 Hall-Sears Model HS-10	635
1 Sprengnether L. P. Vertical	940
Magnetic Tape Recorders	
1 Ampex 601-2	895
1 Ampex 352 (Top plate only)	995
Accessories	
Power Supplies & Chassis	360
Head Cables	354

1 Direct Reproduce Amplifier 4 FM Reproduce Amplifier 3 Power Supplies	4075
1 Engine Generator	295

Appendix
ABSTRACTS OF REPORTS PREPARED UNDER SPONSORSHIP OF CONTRACT AF 19(604)-6642

H. J. Bugajski and D. E. Willis, "An Auxiliary Instrument for Monitoring Seismic Signals," Earthquake Notes, March 1961, Vol. 32, No. 1, pp. 1-4.

The design and use of a visible writing recorder used to monitor seismic signals are described. This instrument was constructed for use as an auxiliary instrument to be used in connection with the magnetic tape recording of seismic signals. Other applications are discussed. A typical explosion recording is presented. Seismic background noise measurements obtained from such a recorder made at widely distributed sites are also shown.

G. E. Frantti, D. E. Willis, and James T. Wilson, "The Spectrum of Seismic Noise," Bull. Seis. Soc. Am., January 1962, Vol. 52, No. 1, pp. 113-121.

The spectrum of seismic noise in the frequency range 0.5 to 31.5 cps is presented graphically for a number of sites over a wide geographical range. Except for a small anomalous effect near 2 or 3 cps, the ground particle motion curves are observed to decrease smoothly with increasing frequency at a rate approximately proportional to the second power of frequency. The curves steepen at frequencies below 1 cps.

G. E. Frantti, "Seismic Energy From Ripple-Fired Explosions," presented at the meeting of the Eastern Section Seis. Soc. Am., Cincinnati, Ohio, November 12, 1962; to be published in Earthquake Notes.

Estimates of seismic energy in body and surface waves for a few ripple-fired explosions are presented. The data indicate that the S/P energy spectrum and the total seismogram energy spectrum are changed significantly by certain normal variations in ripple blasting. Absolute energy estimates suggest that small explosions are more efficient generators of seismic energy, and that from 0.003 to 2.0% of the available energy goes into seismic waves for the cases studied.

H. N. Pollack, "Effect of Delay Time and Number of Delays on The Spectra of Ripple-Fired Shots," Earthquake Notes, March 1963, Vol. 34, No. 1, pp. 1-12.

A theoretical discussion and some observed results are presented for the use of Fourier techniques in the analysis of seismic signals generated by multiple hole blasts. The use of time delays between each hole imparts a periodicity to the seismic signal. Fourier theory shows a relationship between the spectrum of a signal F(t) and the spectrum obtained from a summation of F(t) repeated a given number of times with a fixed time delay between each repetition. This relationship has been observed on seismograms of a series of controlled ripple-fired quarry blasts.

W. C. Meecham and John M. DeNoyer, "Elastic and Acoustic Waves Radiated From Cylindrical Media About a Point Source," University of Michigan Technical Report (to be published).

The theories for three related but different problems are considered. These problems are solutions of the radiation pattern from various types of source media geometries that can be represented by cylindrical surfaces. The first problem considers a point source on the axis of an elastic circular cylinder that is completely surrounded by an infinite elastic medium of differing properties. The second and third problems are for acoustic or fluid media. A free surface has been introduced in both these examples. The half-cylinder problem concerns a free surface containing the axis of the cylinder with the source below the axis and the truncated cylinder problem treats the case of the axis normal to the free surface.

No numerical values have been obtained for the formal solutions presented here.

D. E. Willis and James T. Wilson, "Effects of Decoupling on Spectra of Seismic Waves," Bull. Seis. Soc. Am., January 1962, Vol. 52, No. 1, pp. 123-131.

A series of controlled high-explosive shots was conducted by the Atomic Energy Commission in a salt mine near Winnfield, Louisiana, to investigate seismic decoupling theories. Two recording stations were established by The University of Michigan at various distances between 1.1 and 14.7 km for most of these shots. Frequency analyses of the magnetic tape recordings were made. The results show the relationship of the frequency spectra as a function of charge size, distance from the source, and coupled vs. decoupled shots. The smaller decoupled shots detonated in the large spherical cavities were observed to have somewhat higher predominant frequencies than coupled shots of equivalent size. The reduction in cavity size produced no significant difference in the spectra of the large decoupled shots.

D. E. Willis, "A Note on the Effect of Ripple Firing on the Spectra of Quarry Shots," Bull. Seis. Soc. Am., January 1963, Vol. 53, No. 1, pp. 79-85.

A series of controlled quarry shots were recorded at a distance of approximately 900 feet to ascertain the effect of ripple firing on amplitude and spectra of the seismic waves. A measurable reduction in the amplitude of compressional and shear waves was observed at some frequencies. This effect was not so pronounced for the surface waves.

D. E. Willis, "Travel Times and Ground Amplitudes Toward Nevada Test Site," presented at meeting of Seis. Soc. Am., Los Angeles, Calif., April 1962.

P_n travel-time data obtained from underground nuclear detonations at the Nevada Test Site along a line to the southeast toward Carlsbad, New Mexico, fit an equation of the type

$$P_n - 0 = 7.31 + \Delta/8.0$$

Limited data on a reversed profile obtained from the GNOME shot fit the equation

$$P_n - 0 = 7.28 + \Delta/7.8$$

The rate of attenuation of the peak amplitude for the first half cycle of P_n from the GNOME shot was determined to be slightly greater than the inverse square of the distance. Higher frequencies were obtained for the GNOME shot than were observed for the HARDTACK series. This shot generated compressional waves that had higher-frequency energy than the shear or surface waves. The surface waves were composed almost entirely of frequencies lower than those observed for the shear waves.

D. E. Willis, John M. DeNoyer, and James T. Wilson, "Differentiation of Earthquakes and Underground Nuclear Explosions on the Basis of Amplitude Characteristics," J. Geophys. Res., in publication.

The particle-velocityratios of the maximum shear-surface waves to maximum compressional waves were determined for a large number of earthquakes recorded over a wide geographic range. These results are compared with similar types of data for underground nuclear detonations recorded in the United States. It was found that this technique could be used as a diagnostic aid to distinguish between these two types of source at distances less than 1000 km.

D. E. Willis, John M. DeNoyer, and James T. Wilson, "High-Frequency Energy In Seismic Signals Recorded From Different Type Sources," in publication as a VESIAC Conference Report.

This paper presents data, collected over an eight-year period, that show high-frequency seismic energy contained in signals recorded 100 km or farther from the source. The types of sources treated are earthquakes, nuclear explosions, and chemical explosions. The data are presented in the form of paper seismograms, particle velocity vs. frequency graphs, and power density graphs. It is shown that the frequency content of seismic signals generated by the different types of sources varies considerably.

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14. G. E. Frantti, D. E. Willis, and James T. Wilson, "The Spectrum of Seismic Noise," Bull. Seis. Soc. Am., January 1962, Vol. 52, No. 1, pp 113-121.

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17. H. J. Bugajski and D. E. Willis, "An Auxiliary Instrument for Monitoring Seismic Signals," Earthquake Notes, March 1961, Vol. 32, No. 1, pp. 1-4.

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SEISMIC STUDIES AND EXPERIMENTAL EVALUATIONS
by David E. Willis and James T. Wilson. Final Report.
June 63. 28 p. incl. illus., tables, 18 refs.
(Report No. 3649-22-F)
(Contract AF 19(604)-6642) Unclassified report

An extensive three-year field measurement and data analyses program has been conducted to investigate the frequency and energy spectra, amplitude, and attenuation of seismic signals generated by quarry shots, underwater chemical shots, underground nuclear detonations, and earthquakes. This report summarizes this investigation; a number of technical reports have been prepared which present the data in more detail.

A statistical study of earthquake and nuclear-explosion data revealed that particle-velocity ratios of the maximum
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shear-surface waves to compressional waves can be used as an aid in distinguishing between these two types of source at distances of less than 1000 km. Differences in amplitude, spectra, and energy content of seismic waves were found that could be attributed to source size, depth of source, time duration of source, geological environment at the source and recording station, and azimuthal effects around the source. Since some of the data overlap and conflict, it is difficult to positively differentiate one effect from another. Further investigations of these effects are needed to delineate the useful applications of frequency and energy data for discrimination purposes.

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DESCRIPTORS

Seismic waves
Seismology
Earthquakes
Recording systems
Underground explosions
Nuclear explosions

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shear-surface waves to compressional waves can be used as an aid in distinguishing between these two types of source at distances of less than 1000 km. Differences in amplitude, spectra, and energy content of seismic waves were found that could be attributed to source size, depth of source, time duration of source, geological environment at the source and recording station, and azimuthal effects around the source. Since some of the data overlap and conflict, it is difficult to positively differentiate one effect from another. Further investigations of these effects are needed to delineate the useful applications of frequency and energy data for discrimination purposes.

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DESCRIPTORS

Seismic waves
Seismology
Earthquakes
Recording systems
Underground explosions
Nuclear explosions

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