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OPERATION OF A LONG PERIOD SEISMOGRAPH NETWORK
UTILIZING MAGNETIC TAPE RECORDING AND
ANALYSIS OF DATA RECORDED ON
MAGNETIC TAPE

Paul W. Pomeroy

Lamont Geological Observatory
Columbia University
Palisades, New York

Contract No. AF19(628)-5058

Project No. 8652

Final Report

Period Covered: June 1965-May 1967

1 July 1967

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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PROJECT VELA-UNIFORM

ARPA Order No. 292

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ABSTRACT

The worldwide network of long-period seismographs recording on magnetic tape established under the sponsorship of AF19(604)-8485 has been operated continuously under the present contract. The stations at Mt. Tsukuba, Japan; Honolulu, Hawaii; Uppsala, Sweden; Huancayo, Peru; College, Alaska; Canberra, Australia; and Palisades, New York, have produced large amounts of valuable data.

Many studies utilizing this data have been carried out and several of these are of particular significance to the VELA-UNIFORM program. These include: (1) the relative excitation of surface and body waves by the underground nuclear explosion Long Shot, (2) the magnitude and AR measurements from nuclear explosions and earthquakes in the Western United States, (3) the determination of energy radiation patterns for GNOME, HARDHAT, and the New Madrid and Hebgen Lake earthquakes, (4) the amplitude frequency content and travel times of PcP from nuclear explosions and earthquakes. These studies together with many others utilized the data from this network and indicate the value of this type of recording.

INTRODUCTION

The work statement of this contract reads as follows:

Item 1 - Operate and maintain the worldwide tape recording network for long-period seismic data which was established under contract 19(604)-8485. This network is composed of tape recorders and related equipment at Mt. Tsukuba, Japan; Honolulu, Hawaii; Uppsala, Sweden; Huancaayo, Peru; College, Alaska; Canberra, Australia; and Pallsades, New York.

Item 2 - Analyze the seismic data recorded at the worldwide network stations with particular emphasis on problems associated with the detection and identification of seismic events. This will include the development of new analog, digital and hybrid methods and techniques for the analysis of analog seismic data recorded on magnetic tape.

The seven station network has operated continuously during the entire period of this contract producing a large amount of valuable data. This data together with other data recorded on magnetic tape and on photographic paper has been extensively analyzed with particular attention to the problems of direct interest to the mission of the Nuclear Test Detection Office of the Advanced Research Projects Agency.

These analyses include:

- 1) The relative excitation of surface waves by the underground nuclear explosion LONG SHOT.

- 2) The magnitude and AR measurements from nuclear explosions and earthquakes in the United States.
- 3) Energy radiation patterns for GNOME, HARDHAT and the New Madrid and Hebgen Lake earthquakes.
- 4) The amplitude and frequency content of PcP from nuclear explosions and earthquakes.

These studies, together with others carried out under the support of this contract, are described in detail in a later section of this report.

NETWORK STATIONS

The stations listed in Table I are cooperative members of this network and are fully operational at the present time.

Table I

Station	Latitude	Longitude	Date of Commencement of Operation
Mt. Tsukuba, Japan	36 12 39.0°N	14 06 36.0°E	Aug. 1, 1962
Honolulu, Hawaii	21 19 18.0°N	158 00 30°W	July 15, 1962
Uppsala, Sweden	59 51 29.0°N	17 37 37.0°E	Sept. 7, 1962
Huancayo, Peru	12 02 18.1°S	75 19 22.1°W	Dec. 13, 1962
College, Alaska	64 54 00.0°N	147 47 36.0°W	Dec. 10, 1963
Canberra, Australia	35 19 15.0°S	148 59 55.0°E	Apr. 12, 1964
Palisades, New York	41 00 25.0°N	73 54 31.0°W	June 11, 1962

An outline map showing the locations of the stations listed in Table I is presented in figure 1. At these stations, the instruments are operated entirely by local personnel. Routine maintenance, including cleaning of the recording heads and changing of photographic monitor

records and magnetic tapes, is provided, while unusual maintenance and system upgrading is performed by Lamont Observatory personnel in the course of an annual service trip. Records are routinely mailed to Lamont Observatory for analysis and ultimate storage.

INSTRUMENTATION

The instrumentation operated in this network has been described in detail in the final report on Contract AF19(604)-8485 (AFCRL-65-527) entitled "Establishment of a Long-Period Seismograph Network utilizing Magnetic Tape Recording". Consequently, only a brief outline of the operational equipment will be presented here.

Three component long-period seismometers operating at a free period of 15 seconds are used to provide, through two velocity transducers, two outputs. One of these outputs from each seismometer is fed through a resistive coupling network to a long-period galvanometer operating at a free period of 75 to 90 seconds. The oscillations of this galvanometer are recorded on a three component drum recorder. This output provides a complete monitoring facility to the cooperating station and allows the station to utilize some of the recorded data immediately.

The second output from each seismometer is fed to a Minneapolis Honeywell Deviation Amplifier having a fixed gain of approximately 10,000 and the amplified signal is then recorded on a Minneapolis Honeywell Model LAR-7400 tape recorder. This unit records on 14 inch reels of $\frac{1}{2}$ inch magnetic tape at a recording speed of .06 inches.

second. This allows 16 2/3 days of recording time per tape reel and requires a minimum amount of technician time at the recording site.

The track configurations for these 7-channel systems are given in Table II.

Table II

Channel	Use	Level
1	North-South	High gain
2	East-West	High gain
3	Vertical	High gain
4	Compensation	Unmodulated
5	North-South	Low-gain (x 1/5)
6	East-West	Low gain (x 1/5; + time information
7	Vertical	Low gain (x 1/5)

A schematic diagram of a typical tape recording station is presented in Figure 2.

The timing system utilizes the local clock time and a mechanically keyed time identification system described in the earlier report. This system provides time code information including a station identification number, the year, the month, the day, the hour, and the upcoming minute. The day, hour, and minute codes are applied each day while the entire code is used at the beginning, middle, and end of each tape.

A real time reproduce system has been provided to each station in order that the recordings may be monitored and that the cooperating

station may utilize the tape recordings. These units utilize velocity sensitive heads and provide good output at the .06 inch/second record and reproduce speed.

DATA ANALYSIS FACILITY

With the aid of this contract in conjunction with other contracts, an analog data analysis facility has been established at the Lamont Geological Observatory. The principal purpose of this facility is to analyze the magnetic tape data obtained under this contract.

The equipment included in this grouping consists of the following:

- 1) TR-48 48-amplifier analog computer with high accuracy multipliers and a separate console of five 100-volt, very high accuracy multipliers.
- 2) 1 TR-10 20-amplifier analog computer.
- 3) 1 Technical Products Company spectrum analyzer
- 4) 1 Kay Electric Corporation sound spectrograph.
- 5) 1 ISAC statistical analog computer with tape loop for power spectra and auto and cross correlation analysis.
- 6) 2 Honeywell Model 7400 tape transports with record/reproduce electronics.
- 7) 1 Honeywell tape loop transport for spectrum analyses.
- 8) 1 Dymec DY6654 medium-speed digitization system with punched card/punched paper tape output.
- 9) 1 hand digitizer, laboratory built, with associated electronics and punched card, punched paper tape and electrical analog output.

10) 1 Sanborn 4-channel, hot-pen recorder.

11) 3 Krohn-Hite 330 A-4 low-frequency, band-pass filters.

All of this data analysis equipment has been utilized in the studies to be described.

DATA ANALYSES

Results of all data analyses described here and others are reported in full in the publications listed in the Bibliography of this report. Abstracts of the results of the studies of direct significance are given here.

1) Surface Wave Excitation by the Underground Explosion

LONG SHOT.

One of the most exciting studies carried out under the support of this contract is that of the excitation of surface waves by nuclear explosions and earthquakes. In this section, the results of the study of the relative excitation of body and surface waves by the contained underground nuclear explosion Long Shot and by 29 earthquakes which occurred in the same geographic and tectonic environment are reported. Long Shot, detonated beneath Amchitka Island in the Aleutian Island chain on October 29, 1965, generated surface waves equivalent to those of an earthquake of surface wave magnitude $M_s = 3.9$ based on the records from 56 seismograph stations. The short-period data from the same stations indicated a body wave magnitude $m_b = 5.1$. The 56 stations cover the range of epicentral distances from 2.6° to 73.1° and include 54 stations in North America and azimuths from 10° to 86° and two stations in Asia at azimuths of 244° and 259° . A comparison with data from the 29 earthquakes as well as a comparison with the M_s vs. m_b relationship of Gutenberg and Richter indicated that the surface wave generation by Long Shot

was significantly less than that of earthquakes of comparable body wave magnitudes. Later comparisons of the Long Shot data with the theoretical curve of Carpenter and Thirlaway indicate the close agreement of this detonation to that curve. Since the body waves from Long Shot also contain less long-period energy relative to the earthquakes, it was concluded that Long Shot did not efficiently excite the long-period portion of the seismic wave spectrum. This result is in agreement with the theoretical predictions of Keylis-Borok and indicates the importance of utilizing the entire seismic spectrum for identification techniques.

2) AR Studies and Surface Wave Magnitudes

The results of the Long Shot study indicated that further analyses of the magnitudes and AR for nuclear explosions and earthquakes in the United States should be determined. Surface waves from 4 explosions and 6 earthquakes in the western United States were investigated using the long-period records of 27 worldwide standard seismograph stations in North America. The four explosions (BILBY--13 Sept. 1963; WAGTAIL--3 March 1965; CORDUROY--3 Dec. 1965; BUFF--16 Dec. 1965) were all detonated at the Nevada Test Site. The six earthquakes were distributed throughout the western United States: Palm Springs and San Bernadino, California; Fallon, Nevada; Hebgen Lake, Montana; Dulce, New Mexico; and New Madrid, Missouri. These earthquakes were chosen to provide as wide a variety of geographical and tectonic settings as possible, in contrast to other studies which have tended to utilize many earthquakes in one location. The effect of the depth of focus on surface wave excitation was minimized by using only shallow-focus earthquakes ($h \leq 33$ km.) The earthquakes ranged in body wave magnitude (m_b) from 4.0 - 4.9 and the explosions from 4.8 - 5.6. All of the m_b 's were determined using Evernden's formulae for regional and near-regional distances. When the observed AR data, normalized to a common body wave magnitude, are plotted as a function of epicentral distance for the 10 U.S. events, the data for the earthquakes do not separate distinctly from the explosion data; but the explosions generally generated less surface wave energy than most of the earthquakes.

3) Short-Period Seismic Energy Radiation Patterns from
Underground Nuclear Explosions and Small Magnitude Earthquakes.

Azimuthal radiation patterns of short-period (0.5 - 2.0 cps) seismic energy obtained from integrals of the seismograms from two underground nuclear explosions and two earthquakes were used to study the propagation and source characteristics of the Pg and Lg phases in the United States. In addition, the energy spectrum was divided into two bands, greater than and less than 1.4 cps, and the ratio of higher-to-lower frequency energy was mapped to study the nature of propagation as a function of frequency. Both the total energy and the ratio showed large fluctuations with azimuth and distance. However, a general correlation was found between the energy and ratio contours and the major tectonic provinces of the United States. This correlation was attributed to focusing, resulting from lateral variations in velocity and to regional differences in attenuation of the seismic energy. The range in the Q values across the United States, based on the assumption of symmetrical surface wave propagation is from 200 to 1000, about a factor of 5. The transverse (T) component showed about the same total energy and ratio contour patterns as the vertical (Z) and longitudinal (L) components. Also, energy contour maps are similar to maps obtained using the maximum amplitudes of the Pg and Lg phases. For the events examined, it seems that the nature and distribution of tectonic features along the propagation path

are more important in determining the resultant radiation patterns than the initial conditions at the source. The particle motion at most stations did not give direct proof for the surface wave nature of the Pg and Lg phases, except that Pg tends to be longitudinal or mixed and Lg transverse or mixed.

4) PcP from Nuclear Explosions and Earthquakes.

A continuing study of the travel times and amplitude and frequency information has been carried out for several nuclear explosions and earthquakes. In an initial study of the BILBY event, PcP was recorded at stations between 19° and 88° and arrived early by an average of 1.80 seconds with respect to the Jeffrey's Bullen Tables. The standard deviation of these data was 0.77 seconds while the corresponding P phases were early by 1.34 seconds. A new model for the mantle based on these data would require a slight increase in velocity somewhere in the mantle. If PcP residuals remained, they would have to be explained by mantle-core boundary changes. If the velocity above the boundary is held at 13.64 km/sec, the depth to the core under North America could not be decreased by more than 10 km. Fuller studies of the WAGTAIL, CHASE III, BRONZE and LONG SHOT events showed PcP arrivals early by about 3.51 seconds while the maximum amplitudes show large scatter. The maximum amplitudes of the PcP phases from these explosions as determined by Fourier transform decrease in amplitude at an epicentral distance around 31° . The initial direction of motion of the PcP phases changes from dilatation to compression when crossing 31° epicentral distance. The minimum in observed amplitudes and the phase change have been interpreted by a new core mantle boundary model with a density ratio of 1.02 in sharp contrast with density ratios of 1.6 to 1.9 proposed previously by Bullen, Jeffreys Birch and others.

5) Analysis of Microaftershock Data from Alaska

Seismologists from LGO carried out a series of field programs in 1964 and 1965 to record microaftershocks following the great Alaska earthquake. Using high-gain, high-frequency (magnification of 2 million at 10 cps) portable seismographs recording on magnetic tape, they were able to record large numbers of very small ($M = -2$ to $+1$) events in a very short time interval. For example, 3 weeks after the main shock, microaftershocks were recorded at a rate in excess of 1000 events/day.

Using the field magnetic tape recordings in conjunction with those of the College, Alaska station (where appropriate), the spatial and temporal distribution of aftershocks and microaftershocks have been investigated in detail. In space, almost all of the aftershock activity is confined to the crust in this region. A comparison of aftershock data in all parts of the world showed that, where depth control was available, aftershocks are principally a crustal process. In time, the large $m_b > 4.5$ aftershocks can be regarded as a non-stationary sequence of independent events in which the frequency $n(t)$ decays according to the equation $n(t) = \text{constant } t^{-1.14 \pm 0.06}$. Data on the combined spatial and temporal distribution of aftershocks indicates that to some extent, they are interdependent events.

b) Relationship of Hypocenters of Earthquakes to the Geology of Alaska.

The hypocenters of about 300 well-recorded earthquakes in mainland Alaska, the Alaska Peninsula, and adjacent offshore areas that occurred during the 10-year period before the Alaska earthquake of March 28, 1964, were relocated using an iterative least-squares method. Most of the corresponding epicenters were located with a precision of about 10 to 20 km. In previous studies of this region errors as large as 100 km were common. Since a large number of events can now be located with a greater precision, many of these epicenters can be related to major geologic and tectonic features. A narrow zone of intermediate-depth earthquakes extends from the Alaska Peninsula to the northern boundary of the Alaska Range province in central Alaska. More intermediate-depth earthquakes occur in this region than in any other part of the United States. The volcanoes of the Aleutian Range fall within the zone of epicenters of the intermediate-depth events. These earthquakes, however, extend about 250 km beyond the northern limits of present volcanism. Similarly, a belt of shallow earthquakes can be traced from the Alaska Peninsula and adjacent offshore areas to central Alaska. This latter belt has a greater areal extent than the zone of intermediate-depth earthquakes. Much of the region that was associated with the aftershocks of the 1964 Alaska earthquake exhibited only minor seismicity during the 10-year

period before March 28, 1964. Hence, very little strain energy was released in this part of the aftershock region during the 10-year interval of this study. The epicenters of several shallow earthquakes occur on or close to the Denali, Castle Mountain, and Chugach-St. Elias fault zones. Most of the epicenters of shallow earthquakes, however, are not associated with known faults. Also, several major faults did not exhibit observable seismicity during this 10-year period.

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FIGURE CAPTIONS

Fig. 1. Outline map showing the locations of the cooperative stations operating long-period seismometers and slow-speed magnetic tape recorders under this contract.

Fig. 2. Typical magnetic tape recording system. Details of timing, etc., vary at the individual stations.

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13. ABSTRACT The worldwide network of long-period seismographs recording on magnetic tape established under the sponsorship of AF19(604)-8485 has been operated continuously under the present contract. The stations at Mt. Tsukuba, Japan; Honolulu, Hawaii; Uppsala, Sweden; Huancayo, Peru; College, Alaska; Canberra, Australia; and Palisades, New York, have produced large amounts of valuable data. Many studies utilizing this data have been carried out and several of these are of particular significance to the VELA-UNIFORM program. These include: (1) the relative excitation of surface and body waves by the underground nuclear explosion Long Shot, (2) the magnitude and AR measurements from nuclear explosions and earthquakes in the Western United States, (3) the determination of energy radiation patterns for GNOME, HARDHAT, and the New Madrid and Hebgen Lake earthquakes, (4) the amplitude frequency content and travel times of PcP from nuclear explosions and earthquakes. These studies together with many others utilized the data from this network and indicate the value of this type of recording.			

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