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COLLECTION AND ANALYSIS OF SEISMIC WAVE PROPAGATION DATA

(Annual Report)

August 1967

Prepared For

Geophysics Division

Air Force Office of Scientific Research

Arlington, Virginia 22209

By

David E. Willis
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Geophysics Laboratory

Willow Run Laboratories

Institute of Science and Technology

The University of Michigan

Ann Arbor, Michigan

Sponsored By

Advanced Research Projects Agency

Nuclear Test Detection Office

Project VELA UNIFORM

ARPA Order No. 292, Amendments 32 and 37

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ABSTRACT

This report summarizes one year of theoretical and applied research on propagation of seismic waves and techniques for analyzing data. The main objectives were to determine the frequency and energy of seismic signatures, and investigate attenuation, patterns of azimuthal radiation from source regions, and methods of determining the type of motion at the source. Natural and artificial sources were studied to develop diagnostic aids for distinguishing between earthquakes and underground nuclear detonations. Equipment for selection, reformatting, and digital-to-analog conversion for digitally recorded LASA data was constructed and is being checked out. Several approaches for using the parallel computational capabilities of optics for LASA data were developed. A study of background noise and reciprocity for teleseismic events as recorded on the bottom of a large fresh water lake has commenced with the emplacement of three-component seismometers in Lake Superior. Array data have been used for crustal studies on the Eastern United States. Digital mode filtering was investigated. A perturbation theory for seismic sources was developed.

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COLLECTION AND ANALYSIS OF SEISMIC WAVE PROPAGATION DATA

1
INTRODUCTION

A program of research into the collection and analyses of data concerning the propagation of seismic waves was conducted at the Geophysics Laboratory of Willow Run Laboratories a unit of the University of Michigan's Institute of Science and Technology, during the one-year period from 1 June 1966 through 31 May 1967. This research was supported by the Advanced Research Projects Agency and was monitored by the Air Force Office of Scientific Research under Contract AF49 (638)-1759. It was a continuation of studies begun under sponsorship of Contracts AF49(638)-911, AF49(638)-1078, and AF49(638)-1170.

The main objectives of the program were to determine the frequency and energy of seismic signatures, study attenuation, investigate the patterns of azimuthal radiation from source regions, and study methods of determining the type of motion at the source. Natural and artificial sources were studied in order to develop diagnostic aids to distinguish between earthquakes and underground nuclear detonations. Equipment for selection, reformatting, and digital-to-analog conversion for the large-aperture seismic array (LASA) data has been constructed and is being checked out. Several approaches for using the parallel computational capabilities of optics were studied for their potential contributions to immediate identification for

digital processing of seismic disturbances. An investigation of seismic background noise and the reciprocity of signal amplitudes for teleseismic events as recorded on the bottom of a large fresh water lake has commenced with the emplacement of ocean bottom three-component seismometers in Lake Superior. Array data from the Michigan Basin through North Carolina have been used for crustal studies. Digital computation of mode filtering to separate recordings of body waves from Rayleigh waves has been investigated. A perturbation theory for seismic sources has been developed.

2
RESULTS AND DISCUSSIONS

2.1. DESCRIPTION OF CONVERTOR

The large aperture seismic array (LASA) data convertor, designed to select and reformat recordings from the LASA digital magnetic tapes is completely constructed. However, the convertor is not yet in use because final optimization of tape readout remains to be accomplished. The logic circuits have been checked and debugged. Originally designed to select LASA data for the investigation of optical processing, the convertor, within reasonable limits, is adaptable for input to any type of digital or analog data handling equipment. The output of the convertor can be recorded on digital or analog magnetic tape, or punched on paper tape, or presented on a CRT. During the recording process continuous monitoring can be performed. While channels or subarray sums are selectively recorded and changed at will, presentations of the output, the record number, parity checks, etc., are given visually, and the input tape can be advanced or reversed to select desired recorded intervals.

Both the projected optical investigations and the logical design of the LASA data convertor a e described in the final report (5178-64-F) on the previous contract. Two new possible approaches to the optical investigations have been developed since. The first, convolution-function spatial filtering, is described in a publication in Applied Optics (see appendix I); the second, developed primarily under another contract, is a simple optical method of obtaining sectional autocorrelograms and retrocorrelograms, which recently have been shown to be interpretively beneficial in oil exploration seismology [1]. Further work during this period has also shown that lensless correlography can be suitably performed with the input as a CRT pattern.

Since the above-mentioned report described the logical scheme of the LASA data convertor, the operational characteristics, described by the designer, Rowland H. McLaughlin, follow.

2.1.1. LASA DATA CONVERTOR

LASA is a long-range seismic detection system, consisting basically of a large number of seismic detectors arranged in geometric patterns. By proper correlation of the data from the individual detectors, the array may be so steered as to have maximal sensitivity in any direction. Proper correlation of the data will also achieve large improvements in signal-to-noise ratio over that available from individual detectors. One of the outputs available from LASA will consist of magnetic tape-recordings of the outputs from the individual detectors, in digital form. The recording format provides that a sample of the data from each detector will be taken every 50 ms and the digitized output from the detectors will be multiplexed together with status information and date-time codes into a form compatible with IBM digital magnetic tape-recordings. The main facets of the format pertinent to the following discussion are:

(1) One sample of data from an individual seismometer is called a data word* and consists of 18 bits**. The data word for a specific seismometer occupies a unique position in each frame.

(2) A frame is one sample of data from each seismometer plus weather and telemetry information. The telemetry provides information for calibration and maintenance.

---

*A word is an ordered set of characters that has at least one meaning, and is stored or transferred by the processor as a unit.

**A bit is the smallest unit of information recognized by the processor.

(3) A record will include two frames plus one header, and occasionally one trailer.

(4) A header containing auxiliary data, including time, date, record identification, and "trailer present" indicator initiates each record.

(5) The trailer consists of auxiliary data to be recorded with an occasional record, and includes the status of each detector, the status of each subarray, and similar information.

The LASA data convertor (figs. 1 and 2) has been constructed for the specific purpose of reformatting LASA magnetic data tapes. It is simpler and faster than a general purpose computer primarily because only the desired data is read from the tape. The unit contains a digital-to-analog convertor as an integral component, and hence the data extracted from the master tape may be provided to the user in either digital or analog form. A block diagram of the system for extracting the appropriate data from the LASA recordings is shown in figure 3.

The unit shown in figure 3 performs three basic functions. First, appropriate data on the LASA magnetic tape is recognized by its position in the tape-recording format and transferred to a core memory unit; second, a signal is generated by the data-transfer unit which may be used for auxiliary functions later, such as placing the LASA data in the proper position on the multiple-channel film (this information is stored in the core memory along with the LASA data); and third, the LASA data and its auxiliary information are read from the core memory on command. An internal command is generated at 50 ms intervals (to restore the real-time correlation of the data samples) whenever stored data are converted to analog signals.

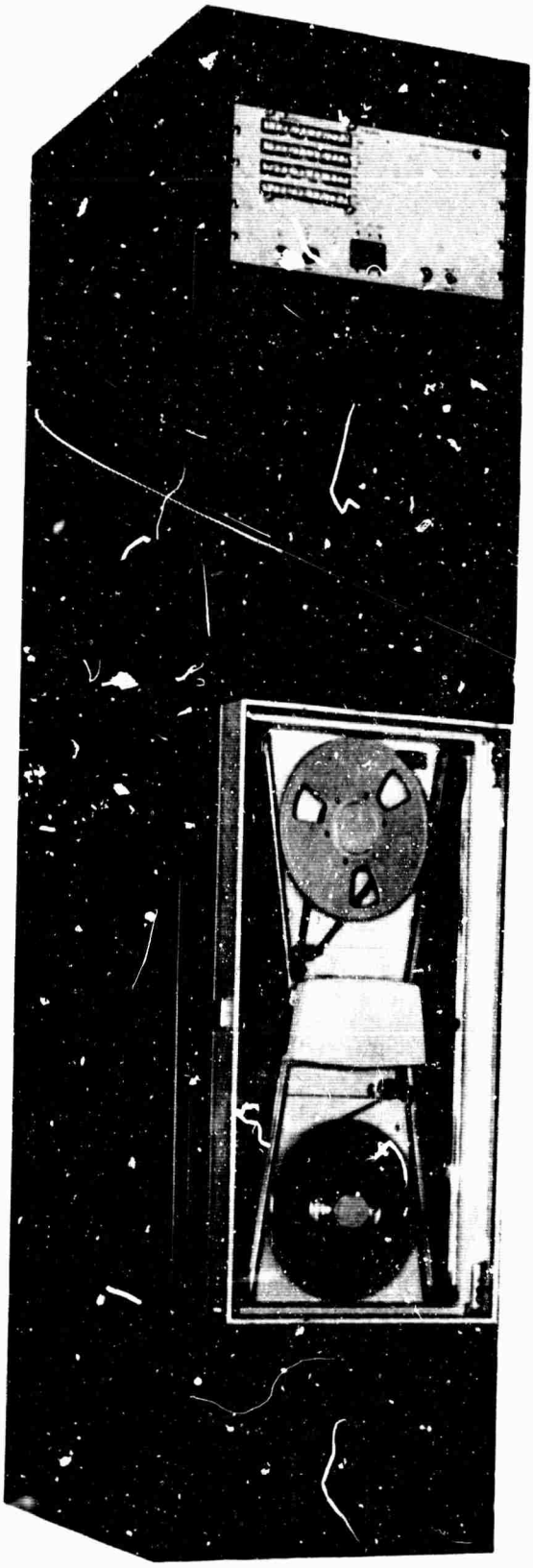

FIGURE 1. LASA Data-Convertor. Tape reproducer and power supply rack.

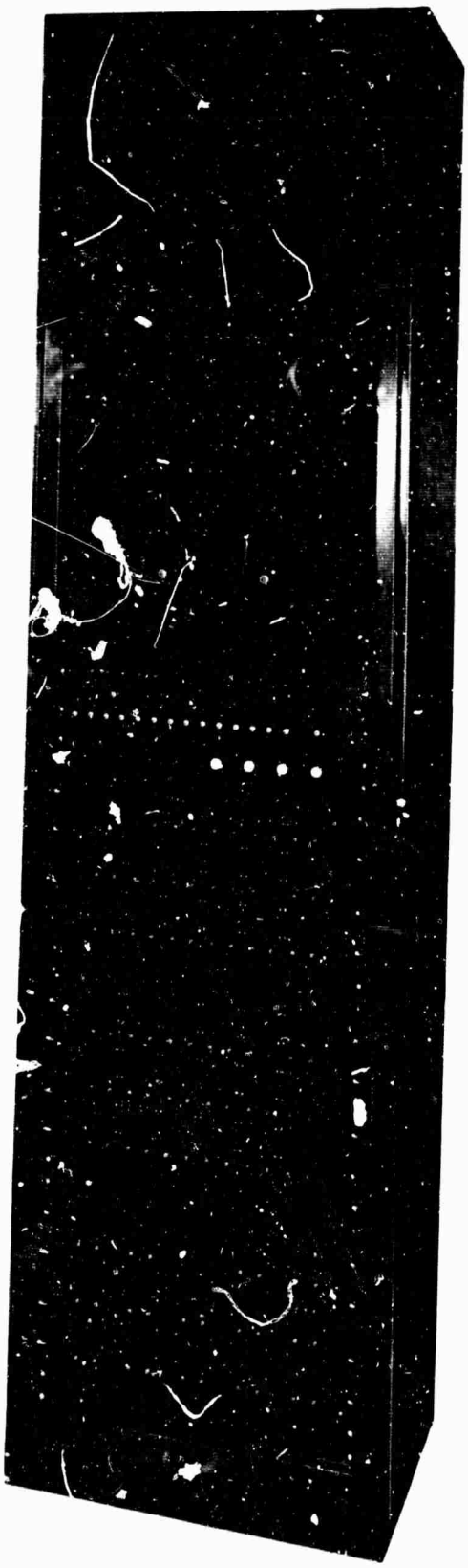

FIGURE 2. LASA Data-Convertor. Data processing rack.

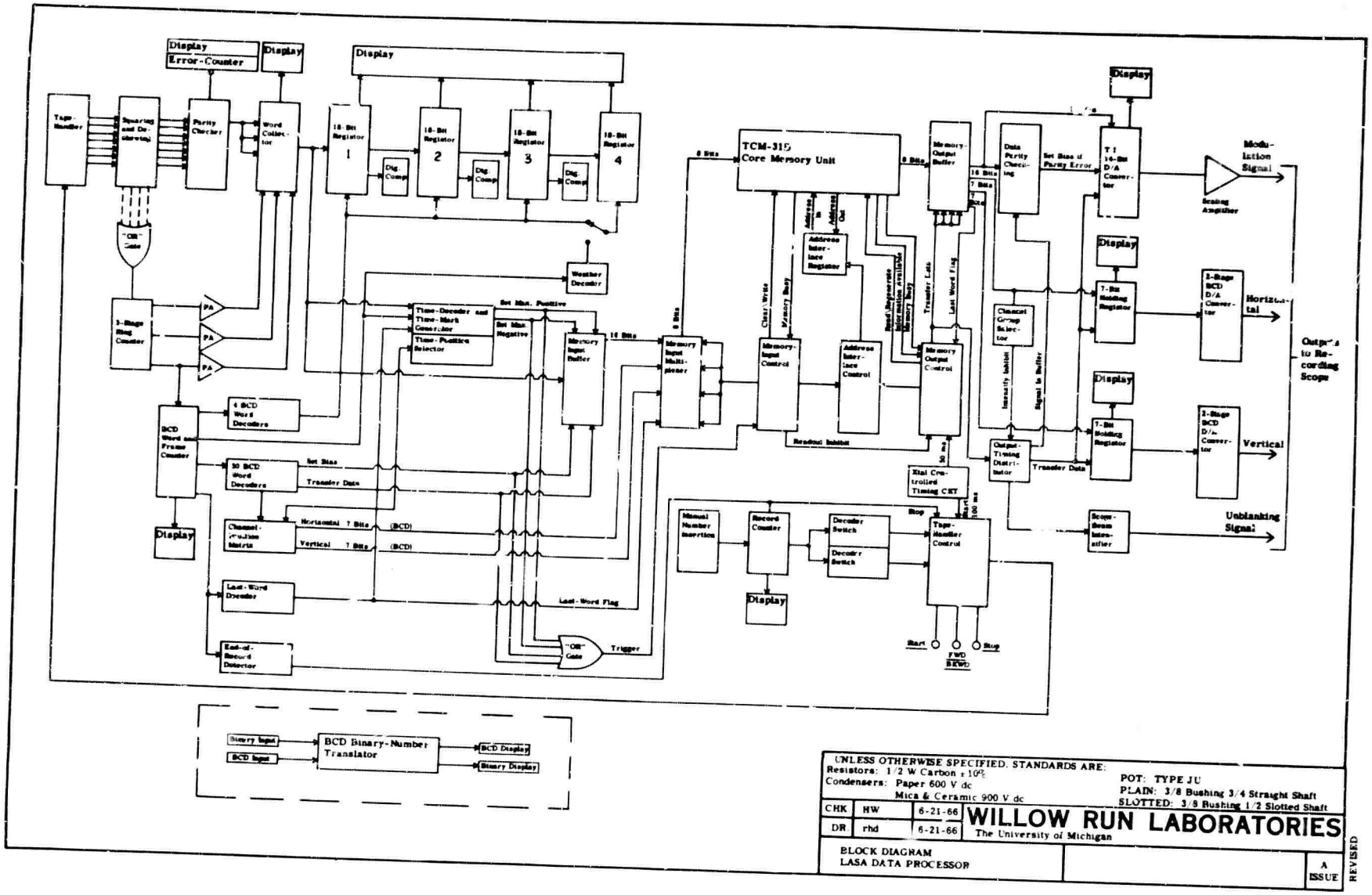

FIGURE 3. LASA Data-Convertor. Block diagram

Auxiliary function of the data-transfer unit are:

(1) Recognizing, counting, and displaying the progression of records during the reproduction of a magnetic tape

(2) Controlling the magnetic tape-transport motion either automatically by use of decoded signals from the tape or by manual control

(3) Displaying selected data contained in header, trailer, telemeter codes, or data words

(4) Decoding and converting the time code to a form suitable for recording on film

Figure 4 shows the controls used to select data which is to be read from the master tape into the core memory of the convertor. As mentioned previously data samples from each seismometer occupy the same unique position in each frame. The selection controls are thumbwheel switches arranged in groups of three. Each thumbwheel is individually adjustable so that each selector group may be rapidly set for any number from 000 to 999. Fifty selector groups are provided and are numbered sequentially and, hence, fifty data samples may be selected by dialing the selectors to correspond with the seismometer number whose output is desired. Using a particular selector group, say number five, also generates a code unique to the selector group chosen, and this code is stored in the magnetic core memory along with the seismometer sample. This auxiliary feature is useful in certain analog applications such as positioning the converted data sample on a film recording or CRT display. Two additional switches are associated with each of the fifty data selector groups. The data-bias switch permits a bias level to be generated for drawing spacing lines on a film recording.

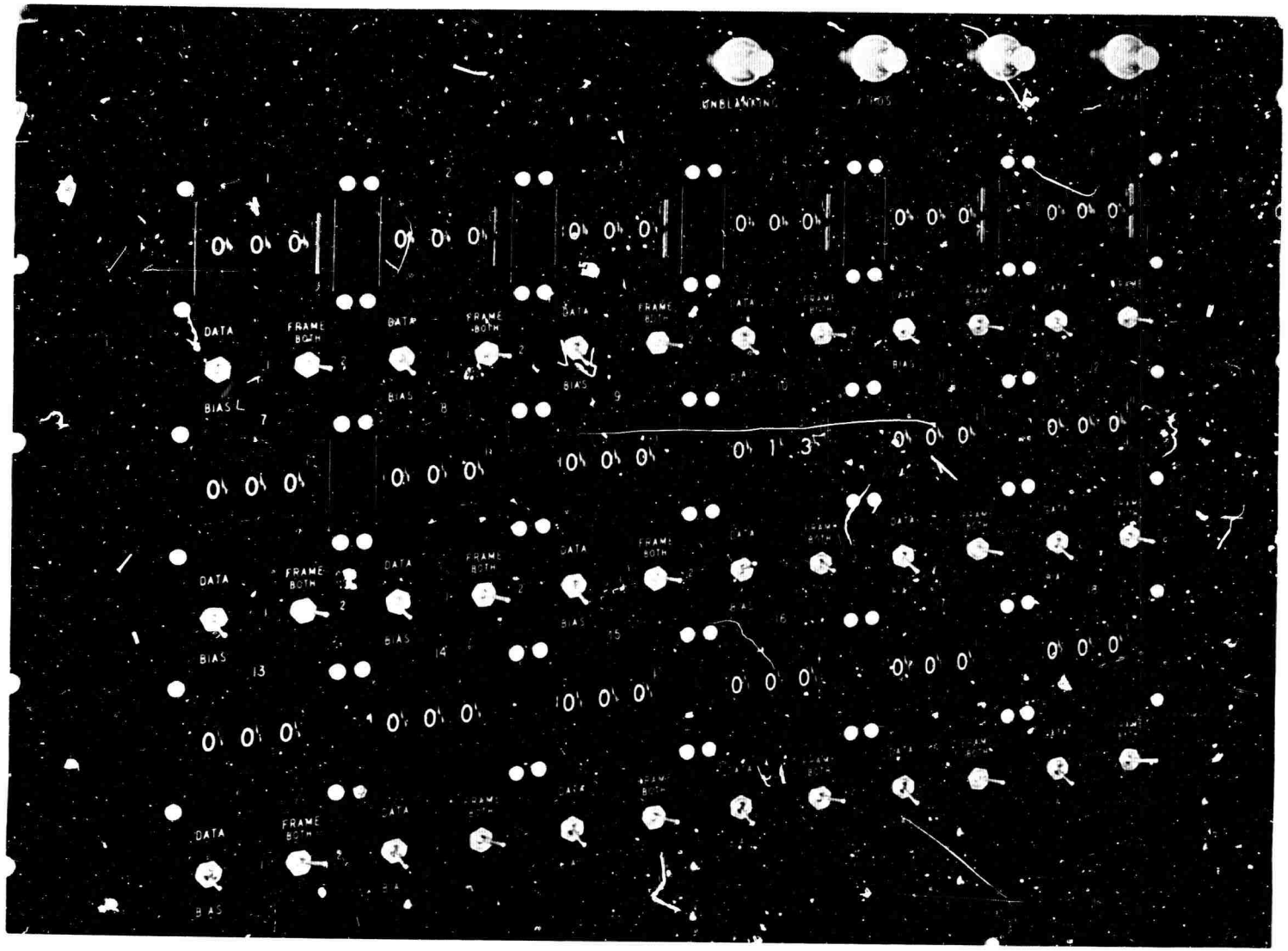

FIGURE 4. Information selection panel.

The frame switch allows the selection of data from frame 1, frame 2, or both depending on the setting chosen.

Consider, for example, that it is desired to select the data in both frames generated by the center seismometer in subarray D4. Consulting the LASA magnetic tape format, D4 is the thirteenth subarray in the sampling sequence, and the center seismometer in each subarray is sampled first. This means that an appropriate selector group, say number 10, is set to 013. The data-bias switch is set to "data" and the frame switch is set to "both". This setting is shown in figure 4. A similar procedure is followed for each data sample desired. The result of such a setting is that each time the master tpae is incremented one record, two samples of data from the chosen seismometer are stored in a known location in the core memory, and are available for readout into any desired device.

The present design of the convertor reads the data out of the core at 50 ms intervals and, by means of the integral digital-to-analog convertor, converts the data to analog form. Other types of readout in analog form, for example, into an analog computer or into an analog magnetic recorder, can also be made. Present facilities only permit time division multiplex readout of multiple samples, however. Of course, a single sample may be selected and a continuous readout obtained. The digital-to-analog converter used has provision for demultiplexing six channels of data into six separate outputs, and if this feature is desired the demultiplexing hardware could be purchase and installed.

If digital output is desired, such as punched paper tape or digital magnetic tape, additional equipment could be added to provide this type of readout.

In addition to the fifty data-word selectors, four additional selectors are connected to storage register-display combinations. These four units shown in figure 5 each contain 18 bits, and each bit controls a lamp. These registers are primarily provided for reading out the header information. However, since the selectors associated with these registers are also adjustable, they may be set so as to read out and display additional data, such as the output from any specific seismometer, or the contents of various portions of the trailer.

The number-four display register is provided with one additional option. A permanently wired weather decoder may be connected to this display. This provision is not merely a convenience but a requirement, since the weather is sub-multiplexed across four records. The details of the multiplexing are contained in the LASA Magnetic Tape Format.

The number-one, number-two, and number-three display registers are also equipped with adjustable digital comparators that permit the operator to search for and control additional functions from particular information.

An auxiliary feature of the LASA data convertor that is provided for operator convenience is the two-way BCD-binary-number translator (fig. 6). This device allows the operator to insert a BCD number, for example, and read the binary equivalent from the display. Thus, a means of rapid conversion from one number system to the other is provided. This unit may also be used to read out and display, for operator interpretation, the information stored in the core memory.

A record counter may be seen in figure 5. This counter counts the number of records processed since the beginning of the tape. This unit also contains provisions for presetting

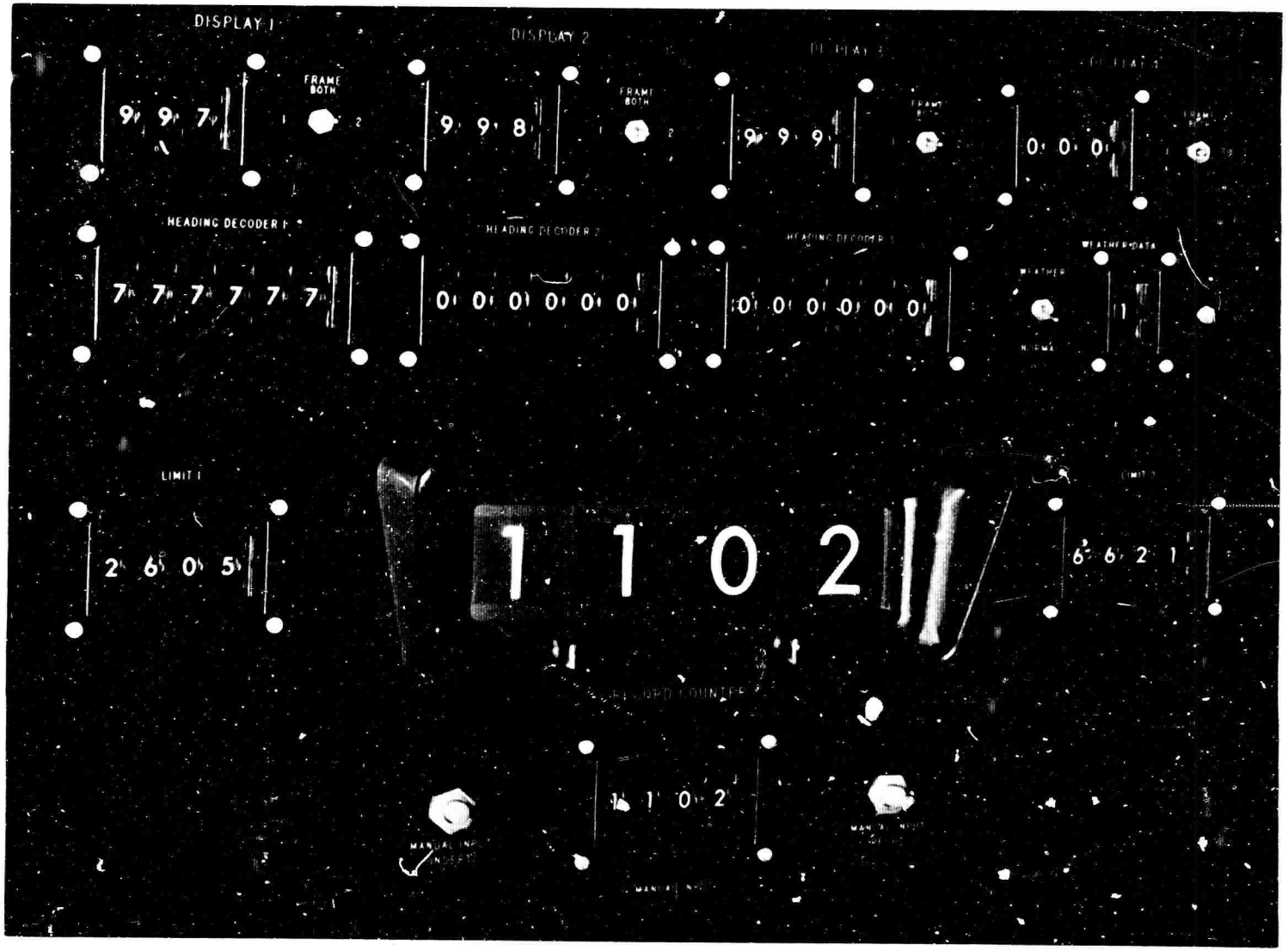

FIGURE 5. Display selector and record counter panel.

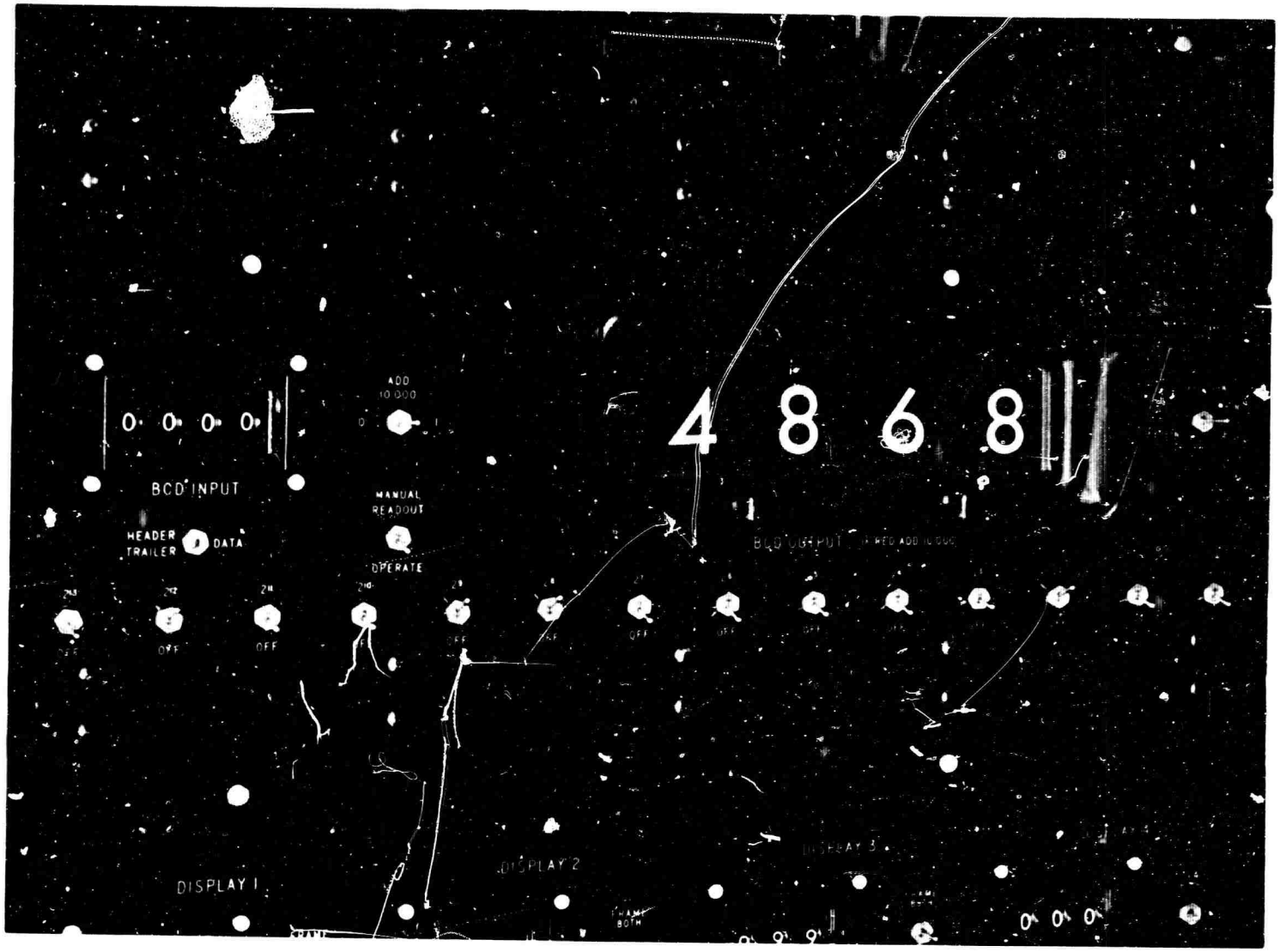

FIGURE 6. Number translator panel.

the counter to any arbitrary number. Associated with the record counter are two selectors that can provide control of the tape's motion. The selectors may be set to any number contained in the record counter. Two such selectors are provided, which permits the unit to be set so as to shuttle between two preset numbers. In addition, manual starting, manual forward-backward, and manual rewinding controls are provided (fig. 7).

2.2. COHERENT OPTICAL PROCESSING

The investigation of coherent optical processing *per se* had been concluded in the previous contract. However, to obtain visual output of the fine frequency structure, operational use of the processor was employed on recordings from three events: LONGSHOT, EARLY RISE, and GREELEY.

As described in the section on earthquake data, the problem on LONGSHOT was to determine the nature of a "pre-PcP" arrival, that is, whether the arrival was a differently refracted P, or was a deep reflection similar to the PcP. To make this interpretation Fourier transforms of six second intervals of the "pre-PcP" arrival, the P and the PcP were made. The frequency distribution of the "pre-PcP" was compared to those of the P and PcP. The fine frequency structure available from the optical Fourier transform was instrumental in indicating that the pre-PcP arrival was most propably a deep reflection.

Portions of the EARLY RISE data were processed to aid in comparison of the consistency of the fine structure from station-to-station across the Michigan Basin, and, along with the GREELEY data, for a comparison with the results of mode filtering

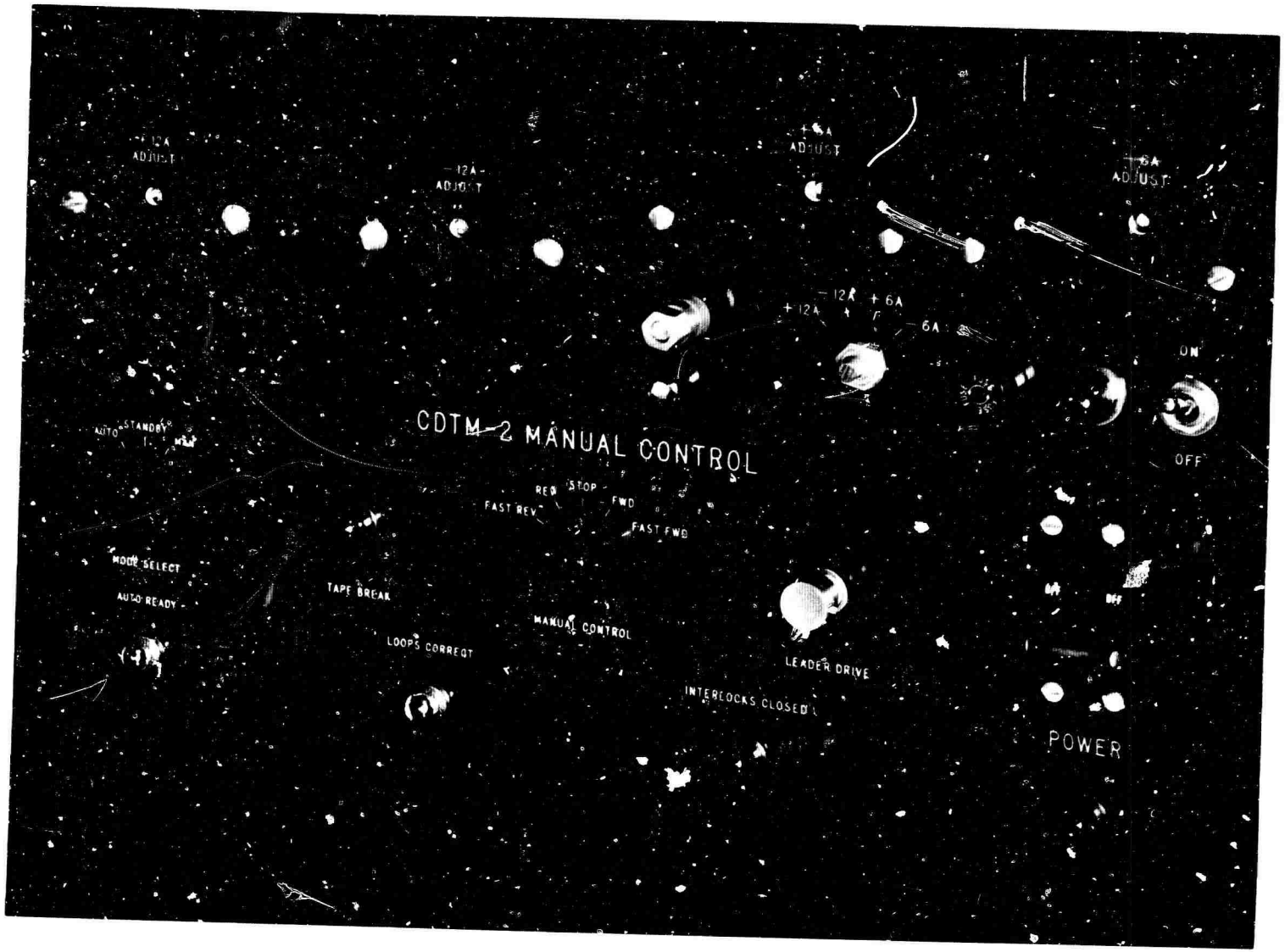

FIGURE 7. Tape transport control panel.

and to determine the effects of crustal variation on the fine frequency structure.

A new method of optical spatial filtering—correlation function filtering—was developed. In this technique the two-dimensional cross- or auto-correlation of two functions is operated upon by selective attenuation. One of the functions is simultaneously imaged, resulting in a "time-domain" equivalent of complex frequency filtering. It is planned to investigate the utility of this technique for processing LASA data. The technique is described in an article in Applied Optics (see appendix I).

2.3. MODE FILTERING

Work has been done on the technique of distinguishing P from Rayleigh-type wave motion using filtering techniques pertaining to the four quadrants of the Fourier-transform plane. Originally done optically on synthetic and empirical data, the mode-filtering process has been adapted to digital computation. The digital approach allows greater flexibility in the interpretation and graphic presentation of the filtered output. Using a program which generates synthetic seismic input, filters it, and reconstitutes the filtered output, contour maps of signal-to-noise ratios for various values of the geometric and signal parameters were produced.

Mathematical analysis has produced analytic expressions for $M(\alpha,t)$ and $N(\alpha,t)$ (c.f., Fifteenth Quarterly Progress Report on contract AF49(638)-1170). The expressions are sufficiently complex to preclude the feasibility of numeric analysis by hand. A computer program was written to calculate values of $M(\alpha,t)$ and $N(\alpha,t)$ so that they can be presented in tabular or a variety of graphical forms.

Hand computation is successful in one case, however, namely that in which signal and noise are of the same frequency and co-directional, and in which the carrier is rotated so that $S_P = S_R = \pi/2$. Let the input vertical signal-to-noise ratio be c'/c, the input radial signal-to-noise ratio be d'/d; then the output vertical signal-to-noise ratio of the signal filtered with $J(\beta,\omega)$ (c.f., Fifteenth Quarterly Progress Report) is

$$\left(\frac{S}{N}\right)_{Z\ out} \approx \frac{\sqrt{\left(c'\right)^2 + \left(\frac{2.95}{\pi}\, d'\right)^2}}{c - \frac{2.95}{\pi}\, d}$$

When $c=c'=3/2$ and $d=d'=1$,

$$\left(\frac{S}{N}\right)_{Z\ out} \approx 3.1$$

which is in close agreement with the experimentally obtained value of about 3 (c.f., Se th Semiannual Technical Summary Report on contract AF49(638)-1170).

2.4. THEORETICAL STUDIES IN ELASTIC WAVE SCATTERING (I. McIvor)

A perturbation method has been developed for obtaining the scattered solution due to imperfections on a plane boundary. It has applications to a number of wave propagation problems of seismic interest. The basic geometry is shown in figure 8. The plane $y=0$ is the nominally plane boundary between two elastic regions. The imperfections in the boundary are defined by $g=g(x)$, which represents the deviation of the actual boundary from the plane $y=0$.

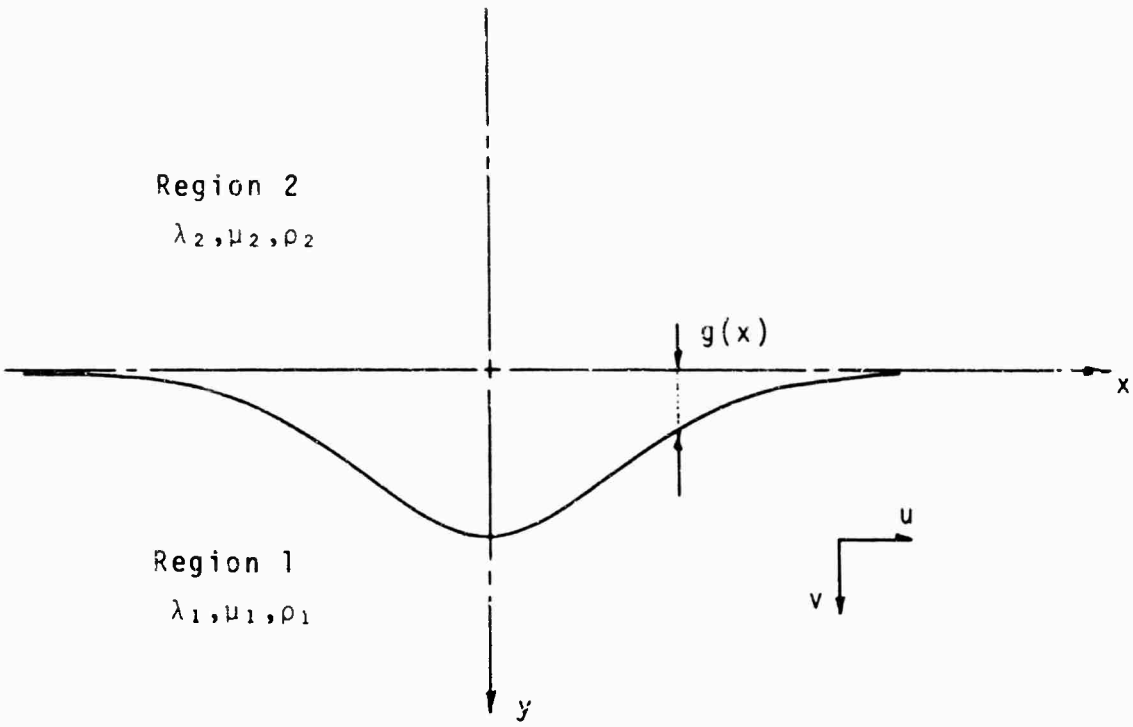

Figure 8

The problem presently being investigated is the reflection of a plane compressional wave by a free surface (i.e., region 2 has zero rigidity). A formal solution has been obtained for the free surface motion for small arbitrary deviations g. When evaluated in specific cases, the results may be of interest in several applications; e.g., the effect of imperfections on the apparent angle of emergence can be determined.

The same approach will give results for a number of similar problems. A solution can be obtained for the effect of imperfections on surface waves. This is of interest in noise studies and possibly would have significance in the attenuation of surface waves. Results obtained by the method for the two-layered region shown in the figure could be applied to reflections from the Mohorovicic discontinuity. The effect of imperfections in the "Moho" on such reflections may contribute to the attenuation of reflected wave phases. It is anticipated that these extensions of the problem presently being considered will be investigated in the near future.

To illustrate the basic ideas of the perturbation method, its formulation in the context of the free surface reflection problem is outlined here. Except for the statement of the boundary conditions, the formulation is identical for the other problems referred to in the previous paragraph.

The displacement components associated with steady-state motion in the x-y plane can be expressed in terms of two potential functions. This representation is with the time factor $e^{i\omega t}$ suppressed

$$u^* = \frac{\partial \phi^*}{\partial x} + \frac{\partial \psi^*}{\partial y}$$
$$v^* = \frac{\partial \phi^*}{\partial y} - \frac{\partial \psi^*}{\partial x} \tag{1}$$

The dilatational and shear potentials satisfy

$$\nabla^2 \phi^* + k_1{}^2 \phi^* = 0$$
$$\nabla^2 \psi^* + k_2{}^2 \psi^* = 0 \tag{2}$$

with

$$k_1^2 = \omega^2/c_1^2, \quad k_2^2 = \omega^2/c_2^2 \tag{3}$$

where c_1 and c_2 are respectively the dilational and shear wave speeds given by

$$c_1^2 = (\lambda+2\mu)/\rho, \quad c_2^2 = \mu/\rho \tag{4}$$

in which λ and μ are Lame's constants and ρ is the mass density.

The solution of (2) representing the reflection of a plane compressional wave by a free plane boundary is given in any standard text on elastic wave propagation. A quantity associated with this solution is denoted here with a subscript zero, e.g., ϕ_0. For the present problem we introduce the scattered potentials as the difference between the actual potentials and ϕ_0, ψ_0. Thus

$$\phi^* = \phi + \phi_0, \quad \psi^* = \psi + \psi_0 \tag{5}$$

where ϕ and ψ are the scattered potentials. The present problem is then defined by the boundary value problem

$$\begin{aligned} \nabla^2\phi + k_1^2\phi &= 0 \\ \nabla^2\psi + k_2^2\psi &= 0 \end{aligned} \tag{6}$$

where the solutions must satisfy the radiation condition and on the boundary $y=g(x)$ the stress conditions

$$\begin{aligned} \sigma_x n_x + \sigma_{xy} n_y &= -(\sigma_{xo} n_x + \sigma_{xyo} n_y) \\ \sigma_{xy} n_x + \sigma_y n_y &= -(\sigma_{xyo} n_x + \sigma_{yo} n_y) \end{aligned} \tag{7}$$

in which n_x, n_y are the direction cosines of the outer normal to the boundary. We let $g(x) = af(x)$ where a denotes a characteristic amplitude of the imperfection. Thus $f(x)$ may be taken as $O(1)$.

The major difficulty of the problem is that the boundary is not a coordinate curve. This can be avoided by an appropriate transformation at the expense of complicating the governing differential equations. If the imperfections are small, however, the transformed equations will involve a small parameter. Thus, they are amenable to perturbation techniques.

The wavelength of the incident wave is

$$K = k_1/2\pi \tag{8}$$

We restrict ourselves to small imperfections, i.e., $a/K \ll 1$, and introduce the small parameter

$$\varepsilon = 2\pi a/K \tag{9}$$

With this a convenient coordinate transformation is

$$\xi = 2\pi x/K, \quad \eta = 2\pi y/K - \varepsilon\zeta(\xi) \tag{10}$$

where $\zeta(\xi) = f(K\xi/2\pi)$. In the ξ-η coordinates the free boundary is given by $\eta = 0$. Introducing the transformation (10) into equations (6) yields

$$\begin{aligned} &\phi'' + (1+\varepsilon^2\zeta'^2)\ddot{\phi} - \varepsilon(2\zeta'\dot{\phi}' + \zeta''\dot{\phi}) + \phi = 0 \\ &\psi'' + (1+\varepsilon^2\zeta'^2)\ddot{\psi} - \varepsilon(2\zeta'\dot{\psi}' + \zeta''\dot{\psi}) + \alpha^2\phi = 0 \end{aligned} \tag{11}$$

where the prime represents $\partial/\partial\xi$ and the dot $\partial/\partial\eta$, and

$$\alpha^2 = c_1{}^2/c_2{}^2$$

The boundary conditions are still given by (7), but are now to be evaluated at $\eta=0$.

We next introduce the expansions

$$
\begin{aligned}
\phi &= \varepsilon\phi_1 + \varepsilon^2\phi_2 + \ldots \\
\psi &= \varepsilon\psi_1 + \varepsilon^2\psi_2 + \ldots \\
\sigma_x &= \varepsilon\sigma_{x_1} + \varepsilon^2\sigma_{x_2} + \ldots \\
\sigma_y &= \varepsilon\sigma_{y_1} + \varepsilon^2\sigma_{y_2} + \ldots \\
\sigma_{xy} &= \varepsilon\sigma_{xy_1} + \varepsilon^2\sigma_{xy_2} + \ldots \\
\bar{u} &= u/(2\pi/K) = \varepsilon u_1 + \varepsilon^2 u_2 + \ldots \\
\bar{v} &= v/(2\pi/K) = \varepsilon v_1 + \varepsilon^2 v_2 + \ldots
\end{aligned}
\tag{12}
$$

The direction cosines are functions of ε. Their power series expansions are

$$
\begin{aligned}
n_x &= \varepsilon\zeta'(1 - 1/2(\varepsilon\zeta')^2 + \ldots) \\
n_y &= -1 + 1/2(\varepsilon\zeta')^2 + \ldots
\end{aligned}
\tag{13}
$$

The stresses σ_{x_0} etc., associated with the perfectly smooth boundary will also be functions of ε when evaluated at $\eta=0$. They can be expanded in power series to yield

$$
\begin{aligned}
\sigma_{x_0} &= \sigma^c_{x_0} + \varepsilon\sigma^1_{x_0} + \varepsilon^2\sigma_{x_0}^{\ 2} + \ldots \\
\sigma_{y_0} &= \varepsilon\sigma^1_{y_0} + \varepsilon^2\sigma_{y_0}^{\ 2} + \ldots \\
\sigma_{xy_0} &= \varepsilon\sigma^1_{xy_0} + \varepsilon^2\sigma_{xy_0}^{\ 2} + \ldots
\end{aligned}
\tag{14}
$$

where, of course, the coefficients on the right hand side are known functions.

When equations (12), (13), and (14) are introduced into (11) and (7), we obtain a series of boundary value problems giving successively higher order approximations. The various order displacement and stress quantities can be expressed in terms of the associated potential functions by introducing equations (12) into the displacement representation and the stress-strain relations. We record here only the first order approximation. It is

$$\begin{aligned} \phi_1'' + \ddot{\phi}_1 + \phi_1 &= 0 \\ \psi_1'' + \ddot{\psi}_1 + \alpha^2\psi_1 &= 0 \end{aligned} \tag{15}$$

with boundary conditions at $\eta=0$

$$\begin{aligned} \sigma_{xy_1} &= \zeta' \sigma_{x_0}^{o} \quad \sigma_{xy_0}^{1} \\ \sigma_{y_1} &= -\sigma_{y_0}^{1} \end{aligned} \tag{16}$$

where

$$\begin{aligned} \sigma_{x_1} &= \mu k_1^2(-\gamma\phi_1 + 2\phi_1'' + 2\psi_1'^{\cdot}) \\ \sigma_{y_1} &= \mu k_1^2(-\gamma\phi_1 + 2\ddot{\phi}_1 - 2\psi_1'^{\cdot}) \\ \sigma_{xy_1} &= \mu k_1^2 (2\phi_1'^{\cdot} + \ddot{\psi}_1 - \psi_1'') \end{aligned} \tag{17}$$

and

$$u_1 = \phi_1' + \dot{\psi}_1, \quad v_1 = \dot{\phi}_1 - \psi_1' \tag{18}$$

with

$$\gamma = \lambda/\mu \ .$$

A solution to this first order approximation has been obtained for arbitrary functions ζ. It has the form of convolution integrals of the imperfection ζ with functions of ξ and η. These

functions are expressed as complex integrals. Although algebraically involved, they can be explicitly integrated by means of contour integration and asymptotic expansions. They are presently being evaluated. When this is carried out, results for specific problems can be obtained. These will be given in future reports.

2.5. FIELD MEASUREMENTS

2.5.1. PROJECT EARLY RISE

Eight University of Michigan field teams participated in the recording of the Lake Superior "Early Rise" shots during July 1966. One hundred and twenty-one sites were located along a southeast line from the Keweenaw Peninsula, Upper Michigan to the North Carolina Coastal Plains. These stations partially reversed a seismic refraction profile obtained from the ECOOE and CHASE shots. The station spacing from $\Delta < 800$ km was approximately 10-15 km. At greater distances a station spacing of approximately 25 km was utilized. At the larger distances two to eight shots or more were recorded at the same site in an effort to obtain reliable data. This was necessitated because of high seismic background noise with resulting poor signal-to-noise ratios. Matched three-component short-period instruments with FM magnetic tape recorders were used at each site.

To date, of the 308 recordings obtained, 296 have been processed and detailed frequency analyses made of 146 recordings. A preliminary report of the EARLY RISE data containing travel times, distances, amplitudes, and predominant frequencies was prepared and submitted to the sponsor previously. Iso-particle velocity maps have been prepared for the vertical and longitudinal components of first P, maximum P and maximum shear-surface wave arrivals at each site. Detailed attenuation studies are currently being completed for these data. Array processing

techniques were employed at five sites using the multiple shots recorded at the same site. Impressive signal-to-noise improvements (a factor of four) were obtained at the most distant site (1680 km) using this technique. However, uncertainties in the preliminary shot point locations degraded this technique so work was suspended pending receipt of corrected shot locations. Now that final shot point locations are available this investigation will be continued.

Travel time studies of the EARLY RISE recordings disclosed an intermediate crustal layer with a velocity of 7.7 km/sec. A mantle velocity of 8.3 km/sec and an upper crustal velocity of 6.2 km/sec were also indicated. Scattered travel time residuals across the Appalachian Mountains make the determination of the crustal thickness uncertain. Lower travel time residuals on the western flank of this range may indicate a change in mantle velocity (8.5 km/sec) or may indicate a thinning of the crustal layer. The larger residuals observed across the crest of the range may be due to a mountain root system such as that observed for the Rocky Mountains.

2.5.2. ECOOE AND CHASE SERIES

Iso-particle-velocity maps have been prepared for the ECOOE shots recorded during 1965. Six stations recorded the CHASE VII event. Detailed frequency analyses have been completed for these recordings. A composite report is under preparation which will present the results of the attenuation and propagation studies using data of the EARLY RISE, ECOOE, CHASE, 1962 North Carolina, and 1963-1964 Lake Superior shots. A presentation of this report is scheduled for the IUGG meetings at Zurich (September-October 1967).

2.5.3. NTS EVENTS

Fifteen NTS events were recorded in Michigan during the past year. Six of these events were recorded at 2 to 5 stations

while the remainder were recorded at only the Botanical Gardens well station. Frequency analyses were performed for 9 NTS events.

2.5.4. EARTHQUAKE DATA

Numerous earthquakes have been recorded on the intermediate-depth well system (Botanical Gardens) during the past year using the anticipator signal threshold triggering device that has been discussed in previous reports. The ESSA Preliminary Determination of Epicenter (PDE) cards received during this period have been scanned and a catalogue of the listed events recorded on the well system was prepared. Unfortunately time and funds have not permitted analyzing much of this data. One particular task which is under study is the determination of the spectral content of compressional waves generated by deep focus earthquakes. It is anticipated that this study will aid in the interpretation of the crustal data (effect of local crustal structure on spectral content of P) obtained from the underwater HE shots detonated during the last five years.

A preliminary examination of passbands from the well system recording of a deep-focus earthquake (2/15/67, Brazil-Peru border, Mag. 6.2, depth 600 km) revealed significant high-frequency (above 6 cps) energy in the P, PcP and ScP phases. Epicentral distance was 53°.

The spectral content of local and regional earthquakes is also under study. Records of the Columbus, Ohio earthquake of April 8, 1967 and the Buffalo, New York quake of June 13, 1967 are being studied. The spectra of these earthquakes will be compared with that of an event recorded prior to the CHASE VII shot in 1966. This event was well recorded at several of the mobile stations deployed for the CHASE shot. Additional records have been obtained from other stations in the region, the epicenter has been located along the Ohio-Indiana border at a distance of about 200 km from Ann Arbor. The magnitude

of this event is about 1.0 on the Richter scale and the large amplitude of S indicates that it may be an earthquake. If so, it is possible that many of the unexplained and often unnoticed small high-frequency arrivals found on short-period records from this region may be microearthquakes. The high background levels make higher station density imperative if these events are to be adequately identified.

An effort to compare the P and PcP spectra of the LONGSHOT event as recorded at stations in North Michigan led to the discovery of an arrival about 15 seconds ahead of PcP and traveling with the same apparent velocity. A search is being conducted to identify this phase on other records and to determine whether it represents a deep refracted path or a reflection from just above the core-mantle boundary. Records of the LONGSHOT event and of intermediate and deep earthquakes in the distance range 55° to 65° have been obtained from the VELA Seismological Center for this purpose.

2.5.5. LAKE SUPERIOR LAKE BOTTOM SEISMOMETER STUDY

In April 1967 two ocean bottom seismometer packages were obtained on loan from the University of California for the purpose of determining the seismic background noise on the bottom of a large fresh water lake and to determine the reciprocity of signal amplitudes for teleseismic events. These units had previously been used in the Pacific Ocean for gathering seismic data for short periods of time.

Earlier in the year personnel of the Geophysics Laboratory made a trip to the Institute of Geophysics and Planetary Physics, University of California to coordinate the details of the instrumentation and underwater techniques. In March 1967, Mr. John Baumler spent two weeks at LaJolla for the purpose of becoming

intimately acquainted with these units as they had been used in the ocean and the methods of dispensing and recovering them at sea.

As received, these units were apparently ready for use under the same conditions which the University of California utilized them in the ocean. For the University of Michigan's program in Lake Superior it was necessary to make some changes to encompass the frequency passband desired and the length of time they must operate underwater unattended. In addition to the above, additional facilities were installed to simplify data reduction.

With the first of several drops in Lake Superior using these packages due in the month of June 1967 it appeared at the time that there would be no problems in implementing this schedule. However, this did not prove to be the case.

The first modification made was in the internal clock unit (SEIKO) used to put time markers on the magnetic recording tape. It was discovered that random clock pulses were being generated and recorded on tape. In order to eliminate this problem it was necessary to incorporate a filter circuit in the clock and also in the tape recorder capstan motor in order to prevent the commutation and speed regulating circuit from interfering with the pulses produced by the clock circuit. The clocks were also modified to provide both minute and hour markers in addition to the original 10 cps and 1 cps pulses. The original 10 cps and 1 cps signals were rectangular pulses approximately 20 milliseconds wide. The "relay box" circuitry of the clock was modified such that the 10 cps signal was converted into a square wave. In addition, the minute and hour pulses were brought out in an "or" configuration instead of a "coincidence" configuration. Both the minute and hour pulses were used to turn "on" a transistor "gate" circuit into which was also fed

the 10 cps signal. When put on one channel of the tape recorder, there then appeared a one-minute time marker, one-second in width filled with the 10 cps square wave. When the hour marker appeared, its duration was one-minute filled with the 10 cps square wave. This was done to give a more accurate determination of time. With the above additions, search and logging time have been greatly reduced in data recovery.

The underwater seismograph units were equipped with Texas Instrument's multichannel type I parametric seismic amplifiers. Input attenuators for these amplifiers were built and installed with the consent of University of California personnel. The parametric amplifier has a basic gain of 60 db followed by a high-cut filter. Two additional fixed 20 db stages of amplifi ion are also included. This facilitates a triple gain feature for each seismometer of 60, 80 and 100 db. These three outputs are recorded on individual channels on the tape recorder.

As used by the University of California, the high-cut filters were set for a 10-second period with a 24 db/octave cutoff. A much higher cutoff frequency was necessary for the Lake Superior program. Hence, values recommended for a 10 cps filter were installed. The best that could be done with these values was a slope of about 16 db/octave. After considerable experimentation it was found that the radial change in resistance value of the RC time constants in the filter circuit affected the transistor biasing and feedback to such a degree that the circuit did not operate to within the stated specifications. By modifying the circuit values in the high-cut filter, the desired 24 db/octave cutoff at 17 cps was obtained with a phase shift between channels of no more than 5 degrees overall. On the application of a signal to the input of the amplifier it was found that as the amplitude of the signal was increased and the three outputs of the amplifier were monitored (60, 80, and

100 db), the first output to overload and distort was the 100 db position. As the signal input was increased by about 6 db the 60 db output became distorted and consequently this in turn immediately distorted the 80 db output. It was found that the output of the high-cut filter was being loaded by the 10,000 ohm input impedance of the tape recorder bias oscillator.

A transistor emitter follower circuit was added between the high-cut filter output and the input of th "low" channel on the tape recorder. This not only prevented loading of the high-cut filter but also provided greater dynamic range to the amplifier.

The three Teledyne Earth Sciences Division Model SD213 "Ranger" type seismometers contained in each of the ocean bottom units were apparently no longer "tuned" to the two-second period as shown in the original specifications sheets. These seismometers are "detuned" by the proximity of magnetic material and/or their relation to each other when placed close together. It was necessary to "charge" each of the seismometers to a longer period than desired, then "discharge" them individually until they were at the correct period so that they could be phase matched to within a few degrees. The orthogonal set of seismometers in the first unit was tuned with a natural period of 1.1 seconds. In addition to the tuning of the seismometers by "charging" them to frequency, a 6 μFD capacitor was placed across each one with the correct damping resistor to give .7 critical damping. A UTC low-pass filter LLP-10 was placed between each of the seismometers and the input to the parametric amplifier. This action insured the prevention of front-end ove load from unwanted high-frequency data prior to the high-cut filter contained in the later stages of the amplifier.

A seismometer mass centering circuit was devised utilizing the calibrate coil in each of the seismometers to insure the

centering of the mass under all reasonable positions of the seismometer and with motor centering voltages as low as 6 V dc.

It was found that of the six seismometers contained in the two underwater packages, two of the units had defective sensing coils. One sensing coil was shorted to the calibration coil and the other sensing coil had shorted turns reducing the coil resistance from 40,000 ohms to 28,000 ohms.

Also two of the individual centering motors had to be replaced because of defective gear boxes. This condition apparently stemmed from the external gear train linkage being coupled too tightly to the mass spring system. The gear teeth were bottomed into each other causing undue friction and wear on the motor gear box and causing the motor to draw more current than necessary to move the seismometer centering system. This was corrected by replacing two of the motors and placing shims under all of the motor mounts as well as slightly moving and lubricating the gears.

Modifications of the Model 96 Texas Instrument's tape recorders were also made. The factory recommended changes included replacing the original Barber-Coleman BYQM-2953 6 V dc tape drive motor with a Sperry-Farragut 12 V brushless dc motor Part No. 490-229. This capstan motor change necessitated the design and installation of a regulated 12 V dc power supply to maintain accurate tape speed. Also included among the recommended changes, was rebuilding the motor mounting flywheel plate and setting the drive linkage wheel bearing in an epoxy mounting.

Under close examination it was found that the flywheels of both tape recorders were out of balance. These flywheels must be critically balanced becaused under dynamic conditions they rotate at 1.6 RPS If left uncorrected, this unbalance could

place an internally generated signal from the tape recorder within the desired information passband.

Due primarily to the increased recording time required for the Lake Superior program (10 to 13 days per drop) it was found necessary to enlarge the battery pack by at least a factor of three in weight. The amount of recording tape and a small increase in electronic circuitry also increased the sphere's overall weight. The increased weight of the underwater package together with the problem of less buoyancy in fresh water requires that an external float system be installed on the sphere for recovery on the untethered drop. This will be accomplished by attaching a cubic foot of Eccofloat PG30 to the package. In fresh water this gives approximately 32 lbs of buoyancy.

The tape playback system has been aligned such that the overall system response is phase matched between .5 and 8 cps.

Three drops were scheduled for the time period June-August 1967. The first two drops are to be tethered drops employing one ocean bottom seismograph while the last drop will utilize both seismographs, one being a free-fall device. The latter is complicated since additional batteries, electronic components, and reduced buoyancy (salt to fresh water) necessitates adding floatation devices and a different anchor release mechanism.

Considerable time and effort was devoted to this task during the last five months. The first unit was placed into operation at 1943 EST on June 5, 1967 with the assistance of the Coast Guard Cutter Woodrush. The drop point was in the vicinity of the EARLY RISE shot point. The unit was recovered on June 15, 1967. The total recording time was 236 hours and 47 minutes. Very high background noise was encountered. Preliminary analyses of the data indicates an average peak ground

displacement of approximately 350 millimicrons at 1 cps and 30 millimicrons at 6 cps. The two high gain data channels for each component were overrecorded most of the time. At three times during the recording period the low gain channel was overrecorded. The first time lasted for six hours, the second for 60 hours and 47 minutes and the last for two hours and 45 minutes. Buildups in background noise of 5 minutes, 1 minute, and 25 minutes preceded these periods. Each period was followed by a decay in background noise lasting several hours or more. At this time it is undecided whether or not this is due to natural background noise or instrumentation problems. The second occurrence began so abruptly that instrumentation problems are suspected. Several smaller gradual buildup and decays in background noise appear to be quite legitimate. The longest one started at 0700 on June 7, 1967 (average background 250 millimicrons), reached a peak at approximately 1630 on June 8, 1967 (average background 2520 millimicrons) and gradually decayed until back to normal at 2300 on June 9, 1967 (average background of 350 millimicrons). Current studies are being conducted to correlate this information with meteorological data and with the land seismic station that was in operation during the same time period.

At least eight events including the Buffalo earthquake of June 13, 1967 were recorded during the first drop.

A second drop is scheduled for July 5th through 17th. Modifications in the amplifiers and damping of the tape recorder base plate mounting system will be conducted before this drop.

2.6. CRUSTAL EFFECTS

Preliminary examination of the EARLY RISE data indicates a considerable amount of scattering with respect to normal attenuation. This phenomenon has also been characteristic of explosion data previously collected in the same geographical area [2]. During earlier experiments shot size, shot location, and station location were all varied thus making it difficult to separate shot and station effects. However, with the EARLY RISE project both shot size and shot location were fixed throughout the entire experiment. This gives one an excellent opportunity to examine station effects. Our attention will be given primarily to the analysis of body waves which have passed through the earth's mantle.

The layers of the earth's crust act as a filter with respect to seismic waves arriving at a given station. As a result the motion recorded at the surface depends not only on the frequency content of the explosive source but also on the response of the layered crust. This dependence gives us a basis for a method of determining the structure of the crust under each station. The analysis of seismic signals for this purpose is best performed in the frequency domain. In order to obtain information which is independent of the frequency of the source, the spectrum of the vertical component of motion is divided by the spectrum of the horizontal component. This ratio represents the tangent of the apparent angle of emergence and it depends only on the angle of incidence of the wave and the system of layers below the recording station. This is assuming, however, that the time window used for analysis contains only reflections and conversions in the station crust.

Since for the most part the upper mantle is homogeneous deep focus earthquakes will give the longest time window for

the direct arrival. In this case, there will be adequate time for the most significant crustal conversions (to SV) and reflections to take place before the next mantle arrival. With body waves from an explosive source recorded at less than 1000 km the situation becomes complicated by the fact that there will be little time lag between the mantle and the first crustal arrival.

The parameters of the crustal model can be determined by comparison of the theoretical and observed spectra of the ratio of the components. The theoretical curves can be calculated easily on a digital computer using a matrix formulation developed by Haskell [3]. The transfer functions for both the horizontal and the vertical component can be calculated as a function of frequency given a model where the compressional velocity, shear velocity, density, and thickness is specified for each layer and an angle is given for the wave incident to the bottom layer. Their ratios give the theoretical tangent of the apparent angle of emergence.

Previous investigations [4], [5], and [6] have been limited to using long-period body waves to determine a one or two layered crust. The source of seismic energy has been limited to deep focus earthquakes. In this study relatively high frequency seismic energy (up to 10.0 cps) will be used to determine a more complicated crustal model with special emphasis placed upon near-surface layering. It is felt that the upper layering contributes most to the nature of high frequency station spectra. It is also this type of layering that could vary radically along the EARLY RISE station line.

In order to use seismic data for crustal determinations good signal to noise is required at all essential frequencies. The EARLY RISE data has adequate signal to noise as far as the Michigan-Ohio border. After this point the acceptable data becomes spotty. The data collected in the Upper Peninsula of

Michigan had exceptional signal to noise but these stations lie too close to the shot point to produce the necessary separation of prominent phases. Thus the greatest portion of usable data was recorded in the Lower Peninsula. The geological setting there is the Michigan Basin structure which through well data is known in great detail. One of the major purposes of this study is to try to correlate the major station anomalies with the Michigan Basin structure.

Due to the complexity of explosion data the crustal structure for the Botanical Gardens station will first be determined using deep focus earthquakes. These should ideally be 100-600 km deep and at a distance not greater than 6000 km. A search has been made of the U.S. Coast and Geodetic Survey earthquake reports for this type of event. Several have been found and a preliminary frequency analysis is being made of each to ascertain the presence and distribution of high frequency energy. The Brazilian-Peruvian earthquake mentioned earlier appears to be acceptable for our purpose. We hope to find at least three or four such earthquakes with some high frequency content. These [illegible] will then be digitized and analyzed for a high resolution of frequency. The observed tangent of the apparent angle of emergence will then be compared with that calculated from a proposed crustal model for the Ann Arbor station.

A preliminary model is suggested on the basis of existing well data. The model consolidates the 20 to 25 known basin layers prior to the basement rock (PreCambrian) into three primary layers. The choice was made on the basis of the degree of velocity contrast between adjoining layers. Depth to the Pre Cambrian structure in the Ann Arbor area is approximately 5000 feet while at the basin center it is over 13,000 feet.

PROPOSED ANN ARBOR MODEL

Layer Number	Rock Types	α-Velocity (km/sec)	β-Velocity (km/sec)	Density (gm/cm³)	Thickness (km)
1	Sandstone (porous) Shale Some Lime-stone	2.8	1.6	2.4	0.29
2	Dolomites, Salts	5.5	3.2	2.8	0.70
3	Limestone, Sandstone (hard)	3.9	2.3	2.5	0.76
4	PreCambrian (Granite)	6.2	3.6	2.6	10.0
5	Unknown	7.7	4.4	2.7	20.0
6	(mantle)	8.3	4.8	3.0	--

Calculations using the Thomson-Haskell matrix formulation and the above model indicate that the basin layers would be sensitive to high frequency seismic energy. Assuming that a consistent model can be found for the well station an attempt will be made to determine the crustal profile along the EARLY RISE station line in the Lower Peninsula. EARLY RISE shot spectrum will all be normalized using the Botanical Gardens records. Any complexities of the explosion data will then be determined. The variations in the ratio spectra from that predicted by the earthquake determined model will be due chiefly to body waves passing through the lower crust. If any discrepancies can be accounted for, corrections can be made to the shot spectrum for each station and the individual station crusts can then be fitted.

Some difficulty may occur in trying to determine a basin model. Fernandez and others have pointed out the complexities that arise when transfer functions are computed at high frequency. This is also compounded with the difficulty in trying to determine a rather complex model. It is expected at least that this endeavor will give some knowledge to the relationship between the amount of data, its frequency content, and the degree of crustal complexity which can reliably be resolved using the spectrum of body waves.

Appendix I

CHRONOLOGICAL ANNOTATED BIBLIOGRAPHY OF REPORTS
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David E. Willis and John M. DeNoyer, "Seismic Attenuation and Spectral Measurements from the Lake Superior Experiments," Am. Geophys. Union Monograph #10, "The Earth Beneath the Continents," 1966.

Detailed attenuation studies of the seismic data obtained from the Lake Superior experiment showed frequent rapid changes in the spectra and maximum amplitudes. In attempting to analyze these data, a technique was developed that permits the presentation of the seismic data in three dimensions: distance, frequency content, and particle velocity amplitude. Contoured iso-particle-velocity maps are thus prepared which show that many of the rapid changes in spectra and amplitude are a part of significant trends extending from more than one shot point. The results show that conditions in the source region for underwater shots strongly influence the character of the seismic waves recorded at considerable distances. Residual iso-particle-velocity maps can help to isolate the shot anomalies and provide considerable insight to the overall pattern of the attenuation of the seismic waves. Using an equation of the type $A = A_0 R^{-n} E^{-\alpha f R}$ to express the attenuation of the seismic waves, values of α - 3 to 5 x 10^{-3} sec/km and n = 1 or 3/2 were formed to give reasonable fits to the observed first compressional wave arrivals. Longer range data obtained from the October 1964 Lake Superior shots indicated a value of $\alpha = 2 \times 10^{-3}$ sec/km and n = 3/2.

John M. DeNoyer, G. E. Frantti, and D. E. Willis, "Short Note on Underwater Sound Measurements from the Lake Superior Experiment," Am. Geophys. Union Monograph #10, "The Earth Beneath the Continents," 1966.

Underwater sound recordings of the Lake Superior shots showed that the predominant energy was contained in a band between 60 and 250 cps. Late arrivals were found that correlate with reflections from the main shoreline, numerous islands, and a few prominent shoals. By recording on magnetic tape and by using various passband filters on the laboratory playback, it was found that more precise times could be determined for the water wave arrivals.

David E. Willis, "A Note on The Comparison of Short-Period Seismometers for Recording Teleseismic Events," Earthquake Notes, Vol. 37, No. 2, June 1966.

Six short-period seismometers of different makes and models, which are in common use, were used to record several underground nuclear detonations at teleseismic distances. A comparison of the seismograms obtained showed no clear superiority of one type seismometer over another. However, arrival times for a given phase recorded by the various seismometers showed discrepancies which could introduce errors in crustal and upper mantle structural determinations.

P. L. Jackson, "Correlation Function Spatial Filtering with Incoherent Light," Applied Optics, July 1967.

The method of lensless correlography (Meyer-Eppler effect) has been extended to image one of the transparencies which are being correlated. An optical filter is placed in the correlation plane, so that the image of the transparency represents the "time-domain" analog of a complex frequency filter.

P. L. Jackson, "Truncations and Phase Relationships of Sinusoids," J. Geophys. Res., Vol. 72, No. 4, 1967, pp. 1400-1403.

The theoretical basis of frequency shifts in the Fourier transform of short segments is given. These frequency shifts arise from constructive and destructive interferences between the positive and negative frequency components of the Fourier transform. Surprisingly, similar shifts are found in electronic bandpass filtering.

D. E. Willis, "A Long-Range Reversed Seismic Profile in the Eastern United States," abstract for presentation at the I.U.G.G. Meeting, Zurich, 1967.

A series of underwater high-explosive shots fired during the past five years have provided data for a reversed seismic profile approximately 2000 km in length. These shots include the 1962 offshore North Carolina experiment, the 1965 ECOOE series, the CHASE III, IV, and VII events, and the Lake Superior shots of 1963, 1964, and 1966. Close station intervals were obtained along the profile. Travel-time curves, frequency analyses and attenuation measurements are presented for these recordings. An intermediate crustal layer with a velocity of 7.7 km/sec was disclosed on the northwestern portion of the profile. Higher P_n velocities and a thicker crust was also indicated. Smaller travel-time residuals across the Michigan Basin were observed on both profiles. The travel-time data indicated a possible mountain root system under the Appalachians. Contoured particle-velocity maps made from the spectral data displosed amplitude anomalies that could be correlated with conditions in the source region. These results aid in the interpolation of the attenuation data.

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13. ABSTRACT

This report summarizes one year of theoretical and applied research on propagation of seismic waves and techniques for analyzing data. The main objectives were to determine the frequency and energy of seismic signatures, and investigate attenuation, patterns of azimuthal radiation from source regions, and methods of determining the type of motion at the source. Natural and artificial sources were studied to develop diagnostic aids for distinguishing between earthquakes and underground nuclear detonations. Equipment for selection, reformatting, and digital-to-analog conversion for digitally recorded LASA data was constructed and is being checked out. Several approaches for using the parallel computational capabilities of optics for LASA data were developed. A study of background noise and reciprocity for teleseismic events as recorded on the bottom of a large fresh water lake has commenced with the emplacement of three-component seismometers in Lake Superior. Array data have been used for crustal studies on the Eastern United States. Digital mode filtering was investigated. A perturbation theory for seismic sources was developed.

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