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AN FM MAGNETIC TAPE RECORDING SEISMOGRAPH

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AN FM MAGNETIC TAPE RECORDING SEISMOGRAPH

Abstract:—A three-component, short-period seismograph has been developed in which frequency-modulated magnetic tape is used as the recording medium. The techniques for maintaining a well-calibrated system under field conditions are discussed in detail. Present methods for editing and conversion to a digital format are also described. The possibilities are explored for a modified system that produces additional long-period information from short-period seismometers.

Résumé:—Une équipe de chercheurs a mis au point un séismographe à courte période et à trois composantes dans lequel se trouve une bande magnétique à fréquence modulée utilisée pour l'enregistrement des ondes. L'auteur explique en détail les moyens techniques employés pour conserver l'appareil bien réglé au cours des travaux sur le terrain. Il décrit aussi les méthodes courantes utilisées pour éditer et convertir les enregistrements à une forme numérique. Il étudie les possibilités de créer un système modifié permettant de tirer des données supplémentaires à longues périodes des séismomètres à courtes périodes.

Introduction

In recent years magnetic tape recording techniques have eased reduction problems and aided the analysis of data in many fields of science. In seismology, tape recording has been used extensively in exploration and crustal studies but seldom in the recording of earthquakes. The recent development of slow-speed recorders with low wow-and-flutter levels has made the recording of earthquake data on unattended magnetic tape both possible and practical.

The instrumentation to be described here has been assembled under a joint project of the Seismology Division, Observatories Branch, Department of Mines and Technical Surveys, and the Arctic Institute of North America.

Some of the numerous advantages of magnetic tape over photographic recording are as follows:

1. Unattended recording periods as long as 30 days are possible. The short tape sections with signals of interest can be re-recorded or physically spliced to a library tape, and the tape can be re-used to reduce costs.
2. Economy in vault construction can offset the high initial capital expenditure. There are operational, research and economic advantages in being able to record wherever there is a suitable seismic foundation without the requirement of dark recording and development rooms.
3. Variable voltage signals can be filtered during playback to remove noise at frequencies outside the pass band of interest. Alternatively, certain frequency components of the signals can be enhanced, for the study of arrival or character.
4. Seismograph characteristics differing from those used during the recording process can be simulated later by using filters and operational amplifiers. Any of the functions available in an analogue computer can be applied directly to the demodulated tape signals.
5. Analogue display of associated signals on multichannel paper recorders allows inspection of adjacent traces for visual correlations in time, frequency and phase.
6. Preparation of large amounts of data for digital computation is easier when the signals are available in the form of variable voltages.
7. Experiments in the aural recognition and detection of events are possible at high playback speeds.
8. With access to a digital computer, research can be conducted into automating the routine search for P-wave onsets and magnitudes now done visually from photographic seismograms.

Although frequency fidelity and amplitude stability are good in most exploration magnetic tape seismograph systems, use of these systems for natural-earthquake recording was not practical until long unattended recording periods with low instrument power consumption became possible. Both direct and FM recording systems have been developed recently for earthquake recording, but IRIG standard FM recording has been adopted for most geophysical purposes in North America.

McLaughlin and Prout (1959) describe an early FM tape recording system and Willis and Johnson (1959) describe analysis of the results using the same system. The latter reference lists in detail the advantages of using magnetic tape. The system was constructed around a basic commercially available recorder which, with a minimum tape speed of $3\frac{3}{4}$ ips, allowed continuous recording for 90 minutes. Dibble (1964) developed in New Zealand a direct recording system from a commercially available recorder considerably modified to record for periods as long as 2 months. Array seismologists require magnetic tape recording to facilitate off-line processing of array data. Descriptions of the array instrumentation used by the U. K. Atomic Energy Authority (Atomic Weapons Research Establishment) are given by Truscott (1964).

Most of the North American systems developed recently have used the IRIG standard. Here, the zero-signal centre frequency produces a constant wavelength on the tape (1.111×10^{-3} in.) irrespective of tape speed. Full frequency modulation is ± 40 per cent. This allows a tape recorded on one IRIG system to be reproduced on any other IRIG system, the data frequencies being shifted by a factor that is the ratio of the reproduce to record tape transport speeds. A number of seismograph systems using IRIG standard FM tape recorders are being developed or used by agencies in the United States, but few descriptions have yet appeared in the literature. One that has been published is the description by Pomeroy (1965) of the Lamont Geological Observatory long-period seismograph network.

Instrumentation

A laboratory layout of a complete set of equipment is shown in Figure 1. The individual components are three seismometers (background), three phototube amplifiers (centre), a slow-speed tape recorder (centre foreground), a chronometer (left foreground), a power supply (behind the chronometer), a control panel (right foreground), and a single-channel pen recorder (behind the control panel). The control panel is shown in more detail in

FIGURE 1. Laboratory layout of magnetic tape recording seismograph.

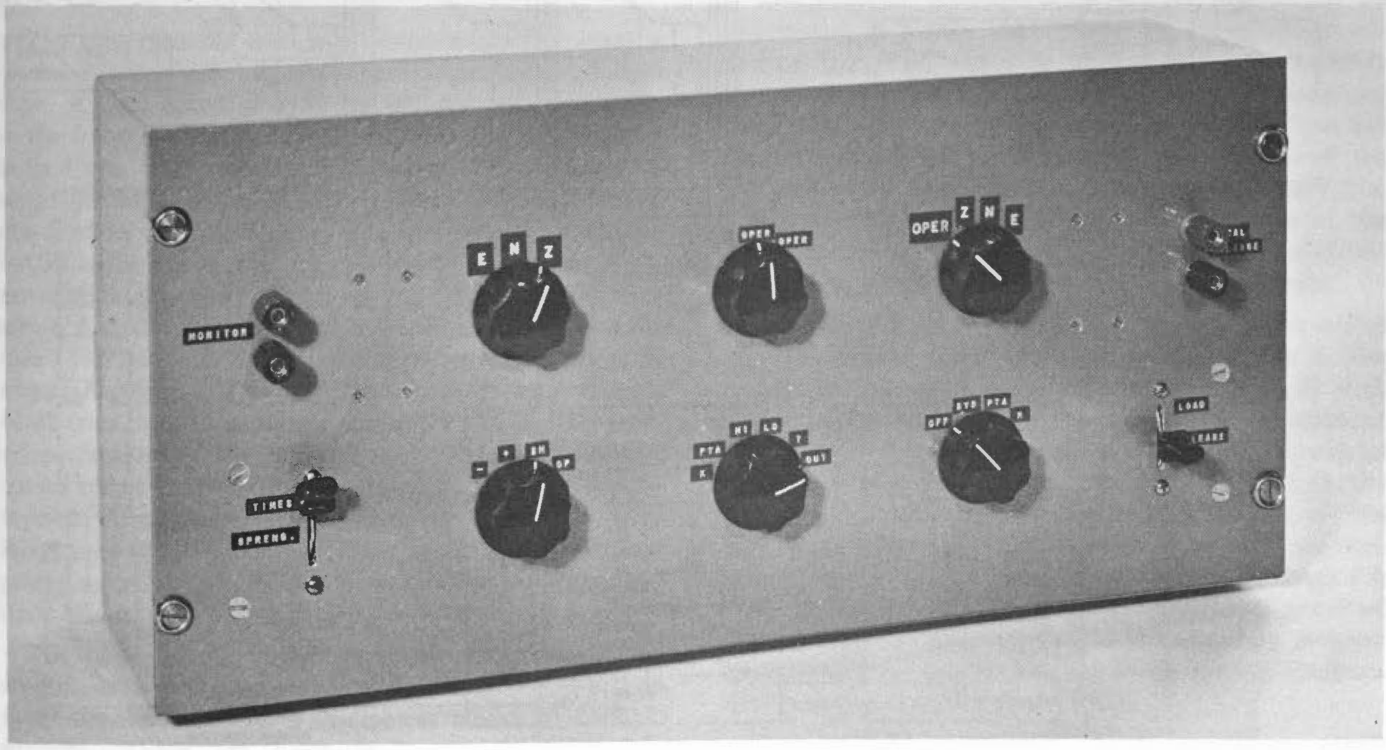

FIGURE 2. Front view of control panel.

Figure 2. Reference will be made to the control-panel circuit diagram, which is shown in Figure 3.

The study for which the first teleseismic tape recordings in Canada were initially intended was one of seismic body waves and their spectral characteristics. Suitable transducers are Willmore Mk II (adjustable period) seismometers with 380-ohm coils. Three seismometers with their periods adjusted to 2.0 ± 0.1 seconds are used to transduce three components (vertical, north-south, and east-west) of surface motion. Damping in the seismometer circuits is adjusted to 0.7 of critical by using variable resistors R18, R21 and R24 (Figure 3). Each of these resistors is then approximately 1,000 ohms. Additional seismometer characteristics will be presented in the discussion of calibration techniques.

Amplifiers with suitable frequency, gain, and stability characteristics are Geotechnical Corporation model 12613 phototube amplifiers (PTA's). The principal features are an 80-ohm bridged-T input attenuator with seven steps of 6 db attenuation plus an infinite (off) and zero position, a main stage consisting of a 5 cps galvanometer with split-beam, dual photocell amplification, an analogue low-frequency amplifier and a 0.01-10.0 cps band-pass filter. Variable resistors R20, R23 and R26 in Figure 3 are set at 80 ohms value to match the 80-ohm bridged-T attenuator so that the galvanometers will be similarly damped (0.9 critical) for all attenuation settings. This leads to a voltage-dividing circuit and a reduction in the possible total gain for the seismograph application. The total gain available in this amplifier is nominally 7×10^5. Power requirement is less than 2 watts at 24 volts DC. The input noise of the amplifier (in the pass band 0.01 to 5 cps) is 0.01 microvolts rms. Since the Willmore Mk II has an open circuit sensitivity of 2 volts per cm/sec, the

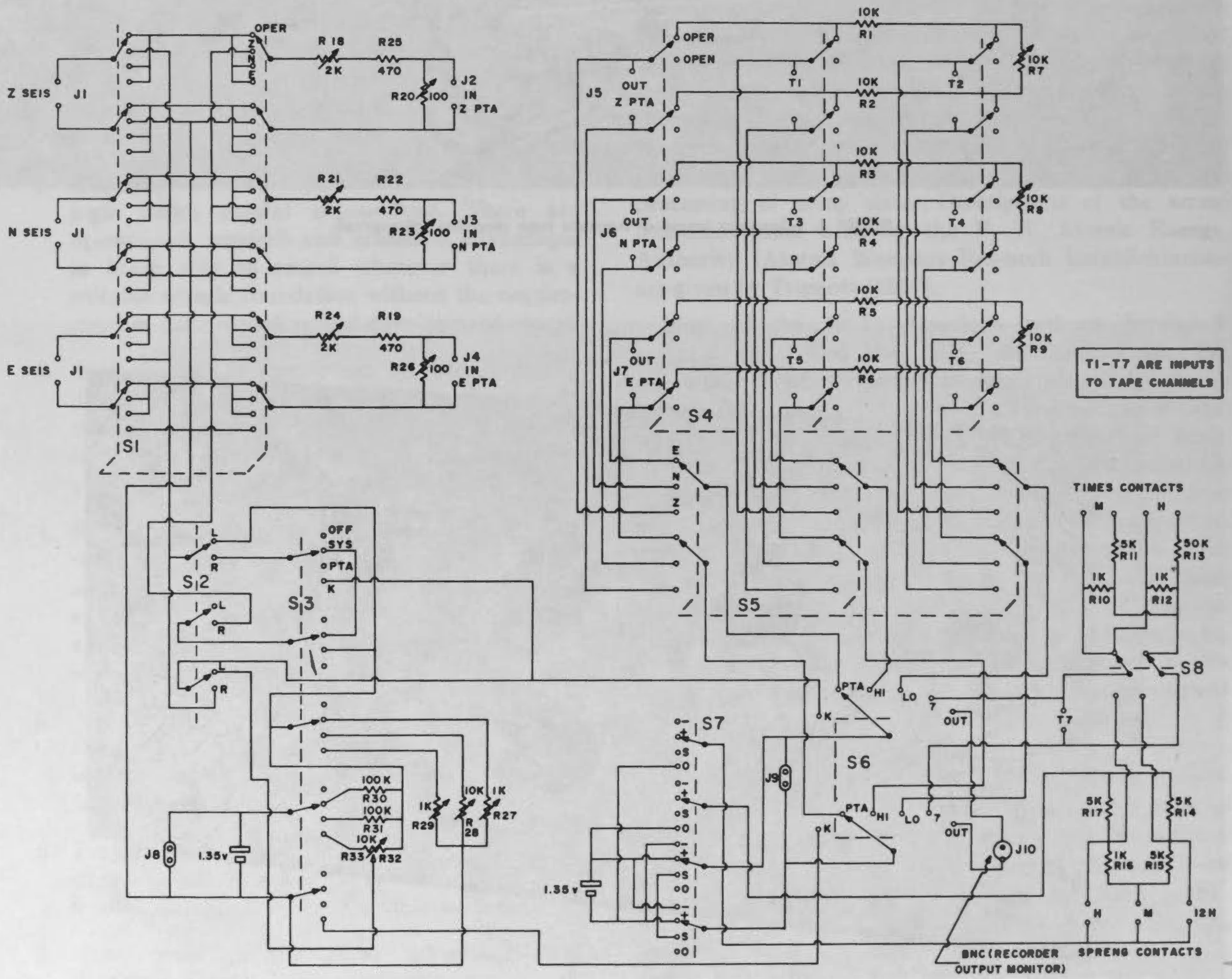

FIGURE 3. Circuit diagram of control panel.

voltage at the input to the amplifier is approximately 42 mV/cm/sec with the damped impedance match. The amplifier noise therefore limits the system to detection of ground velocities greater than about 2.5 mμ /sec.

The limits of available dynamic range are imposed by the nature of FM recording. Full modulation is obtained from a 1.0 volt rms input signal. With the gain such that background noise produces 0.1 volts rms, there is only a factor of 10 in dynamic range. This is insufficient, and it is necessary to record each component signal on two tape channels differing in gain by a factor of 4. The vertical component is attenuated by using fixed resistors R1 and R2 and variable resistor R7 (Figure 3), and the other components similarly.

As will be shown later in the section dealing with the system calibration, the displacement sensitivity at 1 cps on the standard curve (Figure 6) is about 10 volts per micron. The standard curve is 6 db below the maximum system gain. This gain setting was used because the microseismic noise in the field trials undertaken was typically 10 mμ of ground motion. The maximum magnitude earthquake that could be recorded on the high gain channel without saturation was magnitude 5.8 in the 40- to 80-degree epicentral-distance range. By using the output reduced by a factor of 4, earthquakes of magnitude 6.4 could be recorded. In quieter locations, the sensitivity could easily be doubled, and the minimum magnitude earthquake (determined by the amplifier noise level) would be approximately $m = 4.2$.

The tape recorder used is a Geotechnical Corporation model 17373 which records seven channels on 1/2-inch tape. A tape speed of 3/32 ips allowed data recording in the frequency range 0 to 17 cps. The centre frequency is 84.4 cps. The recorder is designed for reel sizes up to 14 inches in diameter; 10½-inch reels of 1.0-mil tape are used in this application, and they allow continuous recording for a period of 5.3 days. Electronics are provided within the recorder for one channel of demodulation and monitor, switchable through all seven channels. The gain of the final output amplifier stage is adjustable from 0.1 to 10. The signal-to-noise ratio is 40 db (rms basis) over the recording pass band. The power requirement of the recorder is 11.6 watts (7-channel record only) at + 12 volts and − 12 volts DC centre-tapped. Advantages of this recorder (compared with laboratory-type instrumentation recorders) are low power consumption, light weight (35 lb) and weather-tight case.

The power supply used for each of the phototube amplifiers is a Technipower model M-23.3-0.100. The tape recorder uses two Technipower model M-13.1-15. supplies. These are hermetically sealed, regulated, overload-guarded, DC sources that operate from mains power. The output voltages are adjustable within a small range of the nominal values.

Two tape channels are used to record each of the three seismic signal components; the seventh is used to record time signals. Circuits are provided within the control panel (Figure 3) to present track 7 with timing pulses from either a Times Chronometer (model TS-3) or a Sprengnether Chronometer (model TS-100). The Times outputs are hour, minute and second (not used) pulses, the amplitudes of which are controlled by the resistors R10-R13. The Sprengnether outputs are adjustable-length, 12-hour, hour and minute contact closures, the DC voltage being provided within the control panel, and the amplitude and polarities being controlled by resistors R14-R17. The Sprengnether is preferable in this application because the 12-hour marks have been found to be useful for tape searching. Both chronometers have stability specifications of the order of ± 1 PPM per week under ideal conditions. Absolute timing is maintained by using time checks from WWV or CHU radio-time-signal receivers. By displaying the chronometer and radio signals simultaneously on a paper chart recorder, accuracies of ± 0.01 seconds can be determined, but the absolute accuracy depends on the chronometer drift over the unattended recording period. There are some timing difficulties in the field owing to mechanical chronometer problems and power failures, but for undisturbed 5-day recording periods the chronometers seldom drift more than 0.3 seconds.

The problem of inaccurate absolute timing will be eliminated in future applications by continuously encoding the radio signal in binary mode (60 markers per minute) directly on the time channel. The accuracy with which absolute timing can be determined from the encoded signal will be limited by the response of the FM recording to the rapid rise time of the binary pip. The upper limit recording frequency of 17 cps of the Geotech model 17373 recorder would allow absolute time to be estimated to better than ± 0.1 seconds.

Extensive monitor facilities have been incorporated into the control panel and are shown in Figure 3. The output of the amplifiers can be monitored at J9 with S6 in "PTA" and S5 in the appropriate component position. The high- or low-gain tape-input signals can be monitored with S6 in "HI" or "LO" and S5 in the appropriate component position. The input of the time channel can be monitored with S6 to "#7" position. Any of the tape output channels is available through J10 with S6 in "OUT"; the channel selection is provided by the recorder monitor switch. An adequate monitor display unit for this system is a single channel Sanborn DC amplifier-recorder model 299.

Switch S7 in conjunction with S6 and S5 can apply four functions—open circuit, short circuit, + 1.35 volts, and − 1.35 volts—to any of the tape tracks for adjustment of recorder electronics. The remaining functions of the control panel—measurement of seismometer K factors and application of a calibration pulses—will be described in detail in the following section.

Calibration

For most purposes it is necessary to know the displacement or velocity sensitivity of each component of the seismograph as a function of wave period—i.e., the microns of ground displacement per volt at the input to the tape recorder at all periods (T) within the pass band of the system. As a check on system performance it is desirable to perform the calibration each time a tape is changed (normally, once every 5 days).

For ease of field calibration it was decided to adapt the pulse-calibration technique of Espinosa *et al.* (1962). A known force is applied to the inertial mass of the seismometer by passing a known direct current through the seismometer, and this force displaces the mass from its equilibrium position. When the seismometer coil is switched from this loading circuit and almost simultaneously connected to the normal recording circuitry, a step-function in ground acceleration is simulated and a damped pulse is recorded. The recorded pulse is inspected at the time for consistency with previous calibrations, but detailed analysis is performed in Ottawa.

Here, selected records are played back onto a visual recorder and digitized onto punched cards by means of a semiautomatic digitizer (Wickens and Kollar, 1966). Once each calibration pulse is in this form, a Fourier Integral Analysis can be performed. The resulting spectrum is in the form of volts per unit rate-of-change-acceleration and, at each period T that is computed, the spectrum must be multiplied by $(2\pi/T)^3$ to obtain the response in volts per unit ground displacement.

To make the over-all calibration absolute, it is necessary to keep a careful check on all quantities that enter into the measurements and reduction. In particular it is necessary to perform an independent measurement of the seismometer constant K—i.e., the seismometer's output in volts when the relative velocity between coil and magnet is 1 cm/sec.

The technique used to determine K is simple in principle, but care with details is necessary to obtain a result with the desired accuracy (about 1%). When the control panel is switched to K measurement (S3 and S6, Figure 3) and a seismometer connected (S1), the circuit shown in Figure 4 is made available.

When the switch S2 is in the "Load" position, the recorder measures a voltage proportional to the loading current I (ma) passing through the seismometer coil of resistance R_c. If I is about 6×10^{-3} ma and the recorder sensitivity 0.01 volts/mm, the measurements are not affected by background noise, nor is the seismometer coil taken out of the region of uniform flux.

Because of the limited dynamic range of the pen recorder, it is important to make the deflection approximately full scale. This is easily done by adjusting R32. The variable resistor R29 serves two purposes: in the loading operation it overdamps the seismometer, and it controls the value of I and hence the amplitude of the undamped oscillations that occur when the switch is flicked from "load" to "release" (Figure 4). By adjusting R29 we can ensure that these undamped oscillations also fill the available dynamic range of the recorder.

The value of K can be determined from the relation

$$K^2 = 2\pi \frac{M}{T} R_x \frac{e_o}{e_d}$$

where M is the seismometer mass, T is the seismometer period, e_d is the seismometer deflection voltage, e_o is the amplitude of the first oscillatory peak for the completely undamped situation, and R_x is given by the relation

$$R_x = R_c + R32 \left(1 + \frac{R_c}{R29}\right) \quad \text{(see Figure 4)}$$

The value of $\frac{e_o}{e_d}$ can be estimated from measurements of

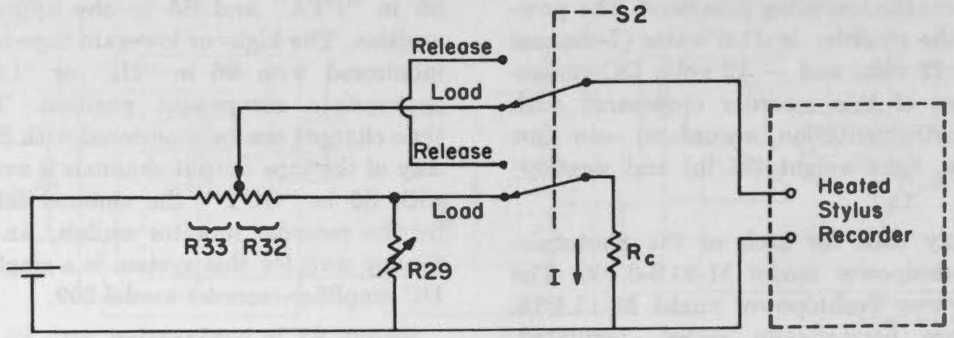

FIGURE 4. Seismometer transducer constant (K) measuring circuit.

the damped oscillation amplitudes. It can be shown that

$$\frac{e_o}{e_d} = \frac{X^{7/2}\,Y^{-1/2}}{Z(X+Y)^2 - X^2(2X+Y)}$$

where $X = B_1 + B_3 - 2B_2$
$Y = 2B_3 - B_2 - B_4$
$Z = 2B_1 - B_d - B_2$

and where B_d, B_1, B_2, B_3, B_4 are measured as shown in Figure 5.

This method of determining e_o/e_d corrects for any linear drift in the heated-stylus recording of the damped oscillations.

In the final calculation of K, the effect of the field operating temperature on the value of the seismometer coil resistance (Rc, Figure 4) is accounted for. The range of the calculated K values for each seismometer over a 5-month field season is about 4 per cent, but any individual calculated value is accurate to within 1 per cent.

To obtain a curve of absolute displacement sensitivity, the following quantities are also required:

1. the input-attenuation settings of the amplifiers during the calibration pulse and during operation;
2. the sensitivity of the digitizer; and
3. the absolute size of the simulated ground acceleration step determined from circuit components.

A sample experimental displacement and velocity sensitivity curve is shown in Figure 6. This is the standard curve for a high-gain channel with the amplifier attenuator set at 6 db. For any particular tape track these curves are adjusted for high- or low-gain tracks, operating attenuation, and individual amplifier gain. The velocity pass band is substantially flat to 13 per cent from 0.3 to 1.5 seconds.

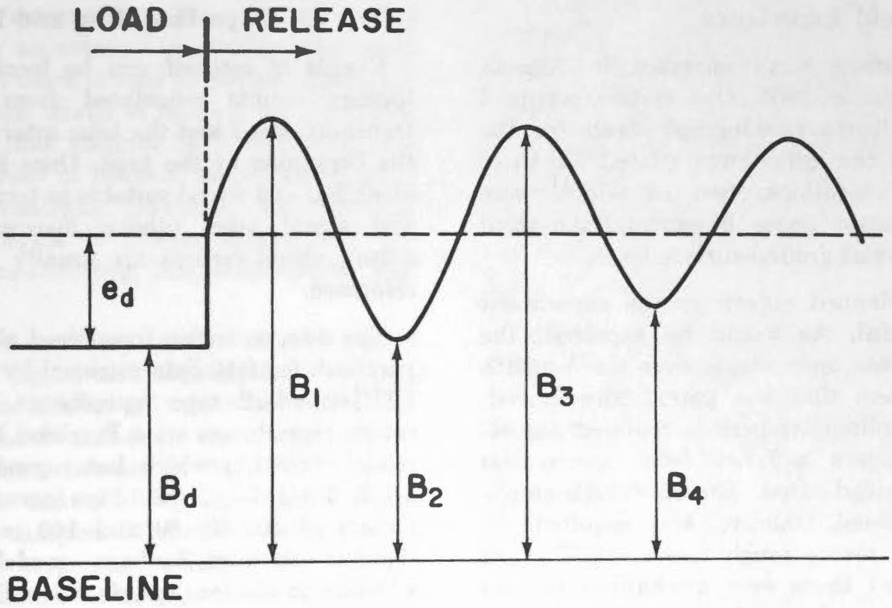

FIGURE 5. Damped oscillation recorded after release of loading current, showing measurements made made for calculation of transducer constant.

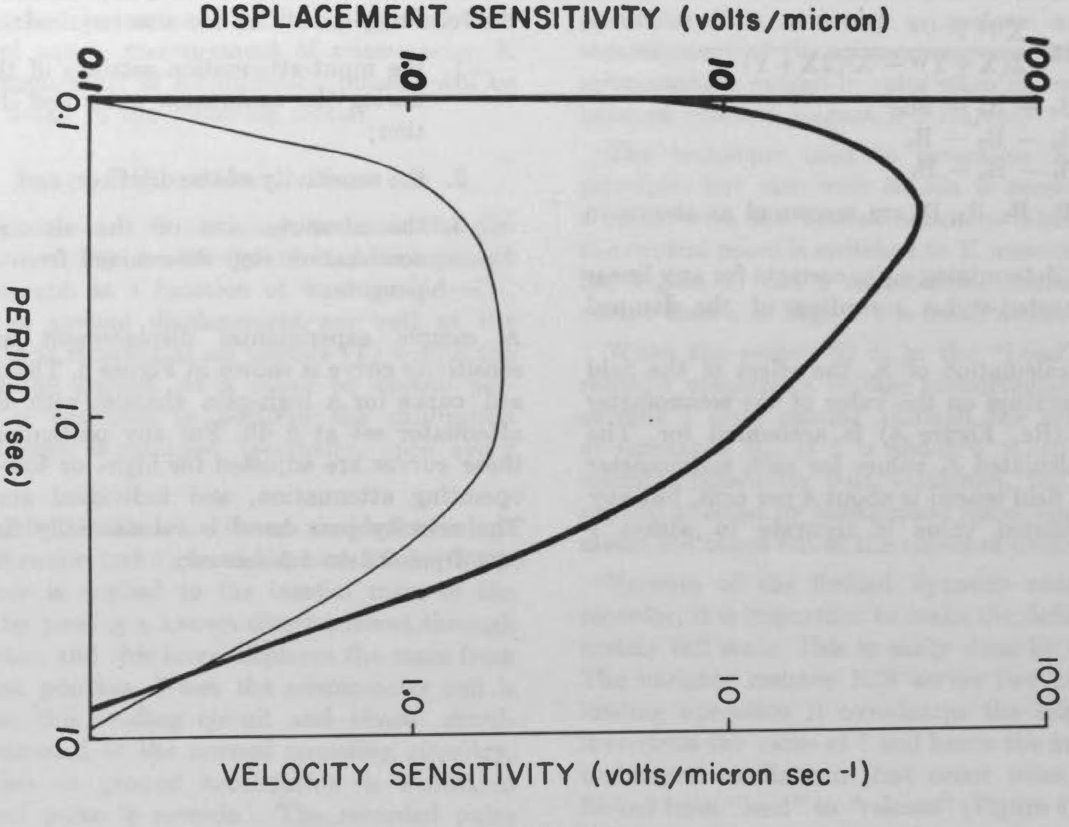

FIGURE 6. Sample experimental displacement and velocity sensitivity curves.

Field Experience

Two identical systems were operated in Alberta locations for 5 months in 1965. One system occupied the University of Alberta seismograph vault for the entire period, while the other was placed in three alternate temporary locations, two of which were concrete floors in vacant house basements, the third a concrete garage floor at ground-surface level.

In terms of the planned objectives the experiment was entirely successful. As would be expected, the undisturbed system was more stable over the 5-month period than the system that was periodically moved. After each move, seismometer periods required adjustment and chronometers suffered from mechanical stoppage of undetermined cause. The phototube amplifiers showed exceptional stability and required re-alignment only after severe rough treatment. Toward the end of the project there were mechanical failures in one of the tape recorders, which required factory modification and repair.

The dynamic range and gain settings were sufficient to record 40 teleseisms on the station pairs in the magnitude range 4.8 to 6.4. These are now the subject of detailed study.

Tape-Handling and Playback

Events of interest can be located on the tapes by footage counts calculated from the recording-tape transport speed and the time interval to the event from the beginning of the tape. Once the events have been identified and found suitable in terms of signal character and signal level (above microseismic and cultural noise), visual records are usually produced for future reference.

The slow recording speed used allows speed-up during playback for fast data retrieval by means of multispeed IRIG-standard tape reproducers. The available laboratory reproducers are a Precision Instrument Company model PS207A, which has reproduce tape speeds of 1-7/8, 3-3/4, 7-1/2 and 15 ips (corresponding to speed-up factors of 20, 40, 80 and 160 respectively); and the Hewlett Packard/Sanborn model 3907A, which, in addition to the four speeds of the PS207A, has speeds of 30 to 60 ips.

This speed-up not only allows data retrieval at speeds much faster than real time but shifts the data frequencies into the normal audio range and allows audio filters to be used for signal enhancement. The seismic frequencies of interest between 0.01 and 10 cps can be studied in the range 6.4 to 200 cps with the variation in speed-up factors available in these reproduce systems. The filter most commonly used is the Krohn-Hite Band Pass model 330-M.

Visual recorders that have been used for playback display are the New Electronics UV Recorder type 1050 and the dual-channel Sanborn DC amplifier-recorder model 322. The Sanborn instrument (a heated-stylus recorder) produces sharper trace contrast, has a higher recording cut-off frequency, and requires no processing for permanent records. A multichannel heated stylus recorder, on which all tape tracks can be displayed simultaneously, will be used in future studies.

Automatic Retrieval and Digitation

Prior to automatic retrieval and digitization of the events, two edit marks (rectangular pulses) are recorded on one of the available edge tracks, designated FM track 8. These edit marks are placed at approximately 1-minute and 2-minute intervals (approximately 6 and 12 inches at record speed) ahead of the onset of the event of interest. Each mark is a 1.4-volt pulse of 1-second duration.

A tape drive-coupled internal- and external-edit sensing circuit has been constructed for the Hewlett Packard/Sanborn 3907A reproducer. When in "drive" mode with the sensing circuit in the "internal" position, tape drive is stopped when the first edit mark is encountered by the read head. If the sensing circuit is now switched to "external" position, "drive" mode can be re-engaged by an external (computer-controlled) relay. The second edit mark is used to initiate automatic digitization of the data tracks of interest for the particular event. As the time interval between the second edit mark and the event of interest can be determined from multichannel analogue playback, the time at which digitization begins is known exactly. In the absence of digital time-encoding, this technique worked most satisfactorily.

The digitizing unit available is an Adcomp 8032A 24-channel analogue/digital and digital/analogue converter. The conversion is from ± 5 volts to 11 bits plus sign binary per channel. Although the sweep rate is 50 Kcps, i.e. 480 microseconds per 24-channel sweep, the actual sample rate is controlled by the time interval between requests for samples. Without devising special timing routines, the maximum sample rate will be limited by the minimum computer clock interval of 1 millisecond. A digital/analogue facility and an eight-channel chart recorder are also available, but this paper will consider only analogue to digital conversion and the storage of digital data on digital tape.

The Adcomp unit also contains 24 computer-controlled relays, which are used to control the tape movement functions of the FM tape reproducer. The system used can digitize any or all of the available eight FM channels.

For the present study a sampling interval of 3 milliseconds with a playback speed of 1 7/8 inch/sec is used. The equivalent Nyquist frequency is 8.3 cps.

The package of "3200 Fortran" and "Compass" subroutines used in the analogue to digital conversion, in the generation of digital tape files, and in the searching and reading of the digital tape is described in the appendix.

Long-Period Information Retrieval

The present equipment was designed primarily for body-wave studies in the period range from 0.2 to 2 seconds. The recording characteristic at longer periods is dominated by the roll-off due to the seismometer. There is evidence, however, that system noise is sufficiently low that useful surface wave information can be recovered by appropriate band pass filtering during playback.

An attempt was made to estimate the noise contribution from the tape recorder by first recording a zero-signal for several hours and then playing back this signal at various speeds on a laboratory tape recorder. The reproduced signal was amplified, filtered through a one-third-octave analogue filter and displayed on a heated-stylus recorder. (A one-third-octave filter is a band-pass filter with steep skirts whose corner frequencies are in a ratio such that their common logarithm is 0.1.) Four filters were available, with centre frequencies of 12.5, 16, 20 and 25 cps, and these together with available playback speeds in the range 15/16 to 60 ips (10 to 640 times record speed), permitted the effective frequency range from 0.02 to 2.5 cps to be studied. Peak-to-peak noise at any one filter setting was estimated by visual inspection of the heated-stylus recording.

This method assumes that the noise is due to wow-and-flutter during record only. However, the contribution from the playback equipment is not negligible, as is demonstrated by recording a zero-signal on the laboratory instrument at all the speeds used during reproduction. The results for both cases are plotted in Figure 7, and two kinds of discrepancy are immediately apparent:

1. Since reproduction at one speed through the 12.5 cps filter is equivalent to reproduction at double that speed through the 25 cps filter, there are several points on the curve where two independent noise estimates are available. If most of the noise was contributed by the record process, these two estimates should be

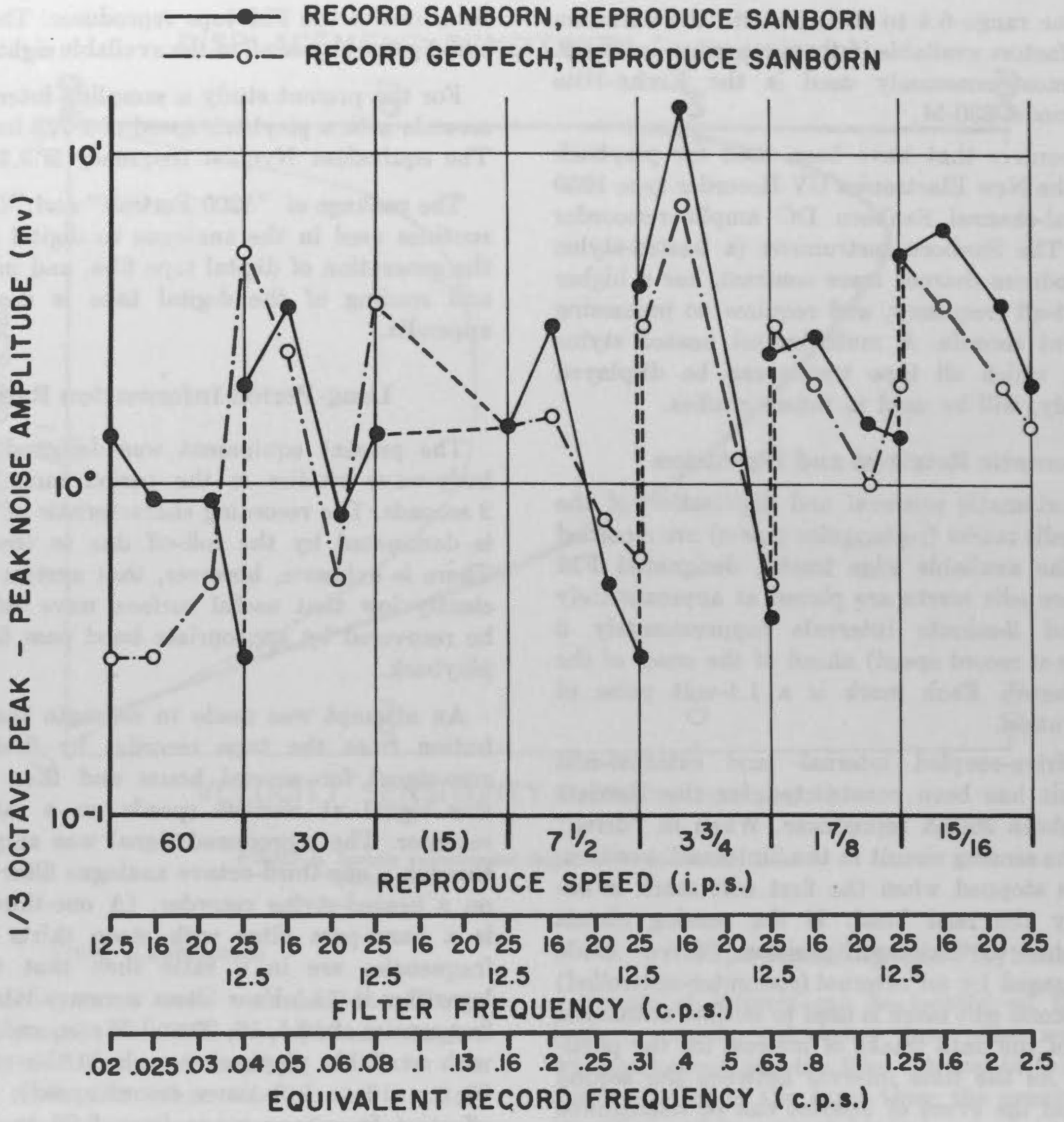

FIGURE 7. Peak-to-peak noise in tape recording and reproduction. (One-third-octave spectrum for a zero-signal recorded on Sanborn model 3907A and reproduced on the same machine; and recorded on Geotechnical Corporation model 17373 and reproduced on the 3907A. The 15 i.p.s. speed was not available on the reproduce machine.)

similar. In fact, they vary considerably, providing independent evidence that the noise added during reproduction is significant.

2. If the noise due to the slow-speed recorder is negligible compared with that from the playback instrument, the records made entirely on the latter should have noise 1.4 times greater than those involving both machines. In fact, the figure is occasionally several times greater. This result emphasizes the variability of noise estimates made from relatively short samples of data.

The results nevertheless provide estimates that are better than an order of magnitude. As an example, we have calculated peak-to-peak noise in the pass band from 12.5 to 50 seconds. This is done simply by taking the square root of the sum of the squares of each one-third-octave contribution in this range. The result is 7 mv peak-to-peak noise in the pass band. The amplitude of ground motion necessary to produce a signal equal to the noise varies as the cube of the period, and with the present system (Figure 6) would range from 0.26 μ at 12.5 seconds to 17 μ at 50 seconds. For a typical shallow earthquake at an epicentral distance of 90 degrees, the surface wave maximum would produce a signal-to-noise ratio of 1 for magnitude 5, and a signal-to-noise ratio of 9 for magnitude 6.

It is instructive to compare these results with the photographic long-period seismographs. A typical long-period system has fairly constant magnification of about 2×10^3 over the pass band considered, and the "noise" is at least 0.2 cm peak to peak. The equivalent ground noise is therefore 1 μ.

It can be concluded that the present short-period seismograph can be adapted to provide additional useful surface-wave information if careful attention is paid to the following details:

1. The Willmore Mark II seismometers might be operated at a natural period of 2.5 instead of 2 seconds.
2. The seismometer-coil resistance should be chosen in such a way that the amplifier-input resistance provides correct seismometer damping.
3. After the amplifier gain is set for short-period work, the long-period output noise from the amplifier alone should be no more than about 1 millivolt. (The phototube amplifiers used in this system may be adequate but were not available for testing at the time of writing.)
4. The noise in available slow-speed tape recorders should be compared. For example, there is some evidence that the PI-5100 recorder manufactured by Precision Instrument Company is better in the long-period pass band.
5. Careful attention needs to be paid to the overall quality of the tape reproduction equipment and to the optimum tape playback speed.

At present, it is desirable to undertake studies at temporary locations in Canada, but impractical with present long-period seismometers. These preliminary measurements indicate that useful results could be obtained as a low-cost adjunct to short-period experiments.

Acknowledgments

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APPENDIX

Description and Lists of Digitization Subroutines

The package of "3200 Fortran" and "Compass" subroutines that were used for digitization of selected FM tape channels, generation of digital tape files, and searching and reading of the digital tape will be described in detail. Fortran and Compass listings of each subroutine with additional comment-card explanations will follow each description. On digital tape, each earthquake is designated as a "file" and each block of data as a "record". All records are buffered onto tape in binary mode.

Subroutine FMDIGIT generates one complete file. It reads an 80-element alphanumeric label from a card that contains the following information in the format shown:

NFILE	file number	1X, I2
EVNT	earthquake number	IX, I2
NSTAT	station number	I2
REGN	geographic region	A7
DATE	year, month, day	2X, I2, I2, I2
TIME	hour, minute, second	2X, I2, I2, I2
ELAT	epicentre latitude	F7.1
ELON	epicentre longitude	F7.1
DEP	focal depth (km)	I4
EMAG	unified magnitude	F4.1
EDINT	playback time interval between start of digitization and first following minute mark (sec)	F4.2
EDINQ	playback time interval between start of digitization and onset of earthquake (sec)	F4.2
DT	digitization interval in record time	F6.4
CHAN	FM tape channels selected as suitable from inspection of analogue records	I4
MMABT	absolute time (hour, minute, second) of first digitized minute mark	IX, I2, I2, I2

The label is buffered onto tape as a 20-element record. CHAN is decoded from the label for selection of FM channels to be digitized. Subroutine FMSTART is called to start the FM tape reproducer. Subroutine WAIT (0) is called for initialization purposes of this subroutine. WAIT (1500) is a delay so that the FM starting transient can die out. Each call to FETCH brings one sample of each of the eight FM channels from the analogue-to-digital converter. After the edit mark has been sensed on channel 8, samples from those four channels designated by CHAN are packed into two words and stored successively in the 1,000-element arrays JARY and KARY. A sampled voltage from one channel (12 binary bits) thus occupies 1/2 computer word and is written as two tape frames. When one of the arrays becomes full it is buffered onto tape as the other is being filled. After 22 data records have been written, an end-of-file is written and the FM tape stopped by a call of FMSTOP. Twenty-two data records thus constitute 11 minutes of original FM tape data starting approximately 1 minute before the onset of the earthquake. Ten minutes of earthquake data will include most short-period phases of interest for teleseismic events. For example, all S phases will be included for events to an epicentral distance of 80 degrees.

```
      SUBROUTINE FMDIGIT
      INTEGER CHAN
      COMMON I1,I2,I3,I4,I5,I6,I7,I8,J1,J2,J3,J4,J5,J6,J7,J8,L1,L2,
    1 M1,M2,M3,M4,NZ(500),NN(500),NE500,NT(500),JARY(1000),KARY(1000)
      DIMENSION JN(8)
      EQUIVALENCE (JN(1),J1)
C                                                    READS LABEL 20A4 FROM CARD AND
C                                                    PUTS IT IN FIRST 20 ELEMENTS OF
C                                                    JARY(I)
```

```
          READ (60,2) (JARY(I),I=1,20)
  2       FORMAT (20A4)
          DECODE (71,999,JARY(1)) CHAN
999       FORMAT (67X,I4)
          BUFFER OUT (01,1) (JARY(1), JARY(20))
          DO 4 I=1,8
          JN(I)=0
  4       CONTINUE
          CALL FMSTART
          CALL WAIT(0)
          CALL WAIT(1500)
          M=0
  5       CALL WAIT(3)
          CALL FETCH
C                                                  FINDS SECOND EDIT MARK BEFORE
C                                                  STARTING DIGITIZING
          IF (J8.LT.00007500B.AND.J8.GE.00004000B) 7,6
  6       M=M+1
          GO TO 5
  7       WRITE (61,8) M
  8       FORMAT (IX,39HNUMBER SAMPLES BEFORE EDIT ENCOUNTERED=,2X,I10)
          IF (CHAN.EQ.2467) 11,9
  9       IF (CHAN.EQ.1357) 15,10
 10       IF (CHAN.EQ.2357) 19,23
C                                                  USES STATEMENTS 11 TO 15-1 FOR
C                                                  LOW GAIN CHANNELS (CHAN=2467)
 11       N=1
 12       DO 13 I=1,999,2
          CALL WAIT(3)
          CALL FETCH
          JARY(I)=J1
          JARY(I+1)=J2
 13       CONTINUE
          BUFFER OUT (01,1) (JARY(1),JARY(1000))
          DO 14 I=1,999,2
          CALL WAIT(3)
          CALL FETCH
          KARY(I)=J1
          KARY(I+1)=J2
 14       CONTINUE
          BUFFER OUT (01,1) (KARY(1),KARY(1000))
          N=N+2
          IF (N.GE.23) 23,12
C                                                  USES STATEMENTS 15 TO 19-1 FOR
C                                                  HIGH GAIN CHANNELS (CHAN=1357)
 15       N=1
 16       DO 17 I=1,999,2
          CALL WAIT(3)
          CALL FETCH
          JARY(I)=J3
          JARY(I+1)=J4
 17       CONTINUE
          BUFFER OUT (01,1) (JARY(1),JARY(1000))
          DO 18 I=1,999.2
          CALL WAIT(3)
          CALL FETCH
          KARY(I)=J3
          KARY(I+1)=J4
 18       CONTINUE
          BUFFER OUT (01,1) (KARY(1),KARY(1000))
          N=N+2
          IF (N.GE.23) 23,16
C                                                  USES STATEMENTS 19 TO 23-1 FOR
C                                                  LOW VERT, HIGH HORIZ (CHAN=2357)
 19       N=1
 20       DO 21 I=1,999,2
```

```
        CALL WAIT(3)
        CALL FETCH
        JARY(I)=J5
        JARY(I+1)=J4
 21     CONTINUE
        BUFFER OUT (01,1) (JARY(1),JARY(1000))
        DO 22 I=1,999,2
        CALL WAIT(3)
        CALL FETCH
        KARY(I)=J5
        KARY(I+1)=J4
 22     CONTINUE
        BUFFER OUT (01,1) (KARY(1),KARY(1000))
        N=N+2
        IF (N.GE.23) 23,20
 23     END FILE 01
        CALL FMSTOP
        RETURN
        END
```

Subroutine RELAYS addresses the computer-controlled relays, which in turn control the FM tape transport functions. The subroutine as shown below is written only for the start and stop functions (entry points FMSTART and FMSTOP), but any or all of the additional functions—reverse, forward, record—could be included by using the appropriate control relay numbers and additional entry points.

```
          IDENT     RELAYS
RELAY     MACRO     (ACT,N)
          RTJ       ADIOS
          IFT       /CLOSE/,ACT,1
          03        N
          IFT       /OPEN/,ACT,1
          04        N
          UJP       *-2

          ENDM
DELAY     MACRO     (DELAY)
          RTJ       ADIOS
          06        -1
          00        DELAY MSEC
          ENDM
          ENTRY     FMSTART,FMSTOP
          EXT       ADIOS
FMSTART   UJP       **
          RELAY     (CLOSE,00)
          DELAY     (5000)
          RELAY     (OPEN,00)
          UJP       FMSTART
FMSTOP    UJP       **
          RELAY     (CLOSE,00)
          UJP       FMSTOP
          END
```

Subroutine WAIT is a delaying routine used primarily to control the time interval between calls for samples. The first time WAIT is called, the computer clock is initialized and control remains in WAIT for the length of time in milliseconds designated by the argument. For each successive call to WAIT, control remains for the total argument time since the preceding call. In this manner the sample interval of 3 milliseconds is obtained.

```
          IDENT     WAIT
          ENTRY     WAIT
WAIT      UJP       **
          LDI       WAIT,1
          LDA,I     0,1
```

```
               SCA        =O77777777
               SWA        WAITIME
TMA            TMA        22B
WAITIME        INA,S      **
               AZJ,GE     GO
UJP            UJP        GO
GO             ENA        0
               TAM        22B
               ENA        TMA
               SWA        UJP
               UJP        1,1
               END
```

Subroutine FETCH uses the system routine ADIOS to call eight channel samples from the converter. It also packs pairs of samples into words in all possible combinations required by the channel selection.

```
               IDENT      FETCH
               ENTRY      FETCH
               EXT        ADIOS
               COMMON
I1             BSS        1
I2             BSS        1
I3             BSS        1
I4             BSS        1
I5             BSS        1
I6             BSS        1
I7             BSS        1
I8             BSS        1
J1             BSS        1
J2             BSS        1
J3             BSS        1
J4             BSS        1
J5             BSS        1
J6             BSS        1
J7             BSS        1
J8             BSS        1
L1             BSS        1
L2             BSS        1
M1             BSS        1
M2             BSS        1
M3             BSS        1
M4             BSS        1
NZ             BSS        500
NN             BSS        500
NE             BSS        500
NT             BSS        500
               PRG
FETCH          UJP        **
               ENI        7,1
               ENA        0
               STA        I1,1
               IJD        *-1,1
               RTJ        ADIOS
               01
               UJP        *-2
               00         I1
               07         8
               PAUS       10B
               UJP        *-1
               LDA        I8
               STA        J8                          I8 PUT INTO J8
               LDA        I2
               SHA        12
               ADA        I4
```

```
        STA     J1          I2 AND I4 PACKED INTO J1
        LDA     I6
        SHA     12
        ADA     I7
        STA     J2          I6 AND I7 PACKED INTO J2
        LDA     I1
        SHA     12
        ADA     I3
        STA     J3          I1 AND I3 PACKED INTO J3
        LDA     I5
        SHA     12
        ADA     I7
        STA     J4          I5 AND I7 PACKED INTO J4
        LDA     I2
        SHA     12
        ADA     I3
        STA     J5          I2 AND I3 PACKED INTO J5
        UJP     FETCH
        END
```

The following four subroutines are used for searching the digital tape, listing portions of the files, and data retrieval during analysis.

Subroutine FINDFILE positions the data tape immediately in front of the file requested by the argument (NWANT) by decoding NFILE from the labels and comparing it with NWANT. It will find a file ahead of or behind the tape position at the time of call.

```
        SUBROUTINE FINDFILE(NWANT)
        COMMON I1,I2,I3,I4,I5,I6,I7,I8,J1,J2,J2,J4,J5,J6,J7,J8,L1,L2,
       1 M1,M2,M3,M4,NZ(500),NN(500),NE(500),NT(500,,JARY(1000),KARY(1000)
        NPAR=0
        JPAR=0
15      BUFFER IN (01,1) (JARY(1),JARY(20))
499     GO TO (500,600,700,800),UNITSTF(01)
500     GO TO 499
700     WRITE (61,701)
701     FORMAT (50H TILT—FINDFILE HAS ENCOUNTERED EOF AFTER A LABEL)
        GO TO 9
800     WRITE (61,801)
801     FORMAT (43H FINDFILE ENCONUTERED PARITY ERROR IN LABEL)
        NPAR=NPAR+1
        IF (NPAR.EQ.10) 9,10
10      BACKSPACE 01
        GO TO 15
9       REWIND 01
        STOP
600     DECODE (3,1234,JARY(1)) NFILE
1234    FORMAT (1X,I2)
        IF(NFILE-NWANT) 30,40,20
20      REWIND 1
        GO TO 15
30      BUFFER IN (01,1; (JARY(1),JARY(1000))
199     GO TO (200,30,15,300),UNITSTF(01)
200     GO TO 199
300     WRITE (61,301)
301     FORMAT (44H FINDFILE ENCOUNTERED PARITY ERROR IN RECORD)
        JPAR=JPAR+1
        IF (JPAR.EQ.10) 11,12
12      BACKSPACE 01
        GO TO 30
11      GO TO 9
40      BACKSPACE 01
        RETURN
        END
```

Subroutine MVOUT is used to list the label and a number of records of a file. The samples are listed in millivolts computed according to the original digitizer sensitivity (± 3777 octal for ± 5 volts). The subroutine as listed below will list the samples contained in the first five data records.

```
          SUBROUTINE MVOUT
          COMMON  I1,I2,I3,I4,I5,I6,I7,I8,J1,J2,J3,J4,J5,J6,J7,J8,L1,L2,
        1 M1,M2,M3,M4,NZ(500),NN(500),NE(500),NT(500),JARY(1000),KARY(1000)
          N=0
          NUT=0
          WRITE (61,30)
 30       FORMAT (1H1)
          CALL READLAB
 28       BUFFER IN (01,1) (JARY(1), JARY(1000))
 3        GO TO (4,10,5,7) UNITSTF (01)
 4        GO TO 3
 5        NWORD=LENGTHF (01)
          WRITE (59,6)
 6        FORMAT (12H EOF UNIT 01)
          GO TO 9
 7        NWORD=LENGTHF (01)
          WRITE (59.8)
 8        FORMAT (12HPARITY ERROR)
 9        REWIND 01
          STOP
 10       CONTINUE
          N=N+1
          WRITE (61,11) N
 11       FORMAT (3(/).1X,13HRECORD NUMBER,2X,I3/)
          DO 12 I=1,999,2
          L1=JARY(I)
          L2=JARY(I+1)
          CALL UNPACK
          II=(I+1)/2
          NZ(II)=M1
          NN(II)=M2
          NE(II)=M3
          NT(II)=M4
 12       CONTINUE
          DO 24 II=1,500
          IF (NZ(II).GE.4000B) 13,14
 13       NZ(II)=NZ(II)+77770000B
 14       NZ(II)=NZ(II)*5000/3777B
          IF (NN(II).GE.4000B) 16,17
 16       NN(II)=NN(II)+77770000B
 17       NN(II)=NN(II)*5000/3777B
          IF (NE(II).GE.4000B) 19,20
 19       NE(II)=NE(II)+77770000B
 20       NE(II)=NE(II)*5000/3777B
          IF (NT(II).GE.4000B) 22,23
 22       NT(II)=NT(II)+77770000B
 23       NT(II)=NT(II)*5000/3777B
 24       CONTINUE
          DO 26 II=1,496,5
          WRITE (61,25) NZ(II),NZ(II+1),NZ(II+2),NZ(II+3),NZ(II+4),
        1 NN(II),NN(II+1),NN(II+2),NN(II+3),NN(II+4),NE(II),NE(II+1),
        1 NE(II+2),NE(II+3),NE(II+4),NT(II+1),NT(II+2),NT(II+3),
        1 NT(II+4)
 25       FORMAT (4X,I5,1X,I5,1X,I5,1X,I5,1X,I5,4X,I5,1XI5,1X,I5,1X,I5,
        1 1X,15,4X,I5,1X,I5,1X,I5,1X,1 I5,1X,I5,4X,I5,1X,I5,1X,I5,1X,I5,1X,I5)
 26       CONTINUE
          NUT=NUT+1
          IF (NUT.EQ.5) 29,28
 29       RETURN
          END
```

Subroutine READLAB reads the label record, decodes the information and prints a black title. A list of the label information has been given with the description of subroutine FMDIGIT.

```
            SUBROUTINE READLAB
            INTEGER EVNT,DATE,TIME,DEP,CHAN
            COMMON I1,I2,I3,I4,I5,I6,I7,I8,J1,J2,J3,J4,J5,J6,J7,J8,L1,L2,
          1 M1,M2,M3,M4,NZ(500),NN(500),NE(500),NT(500),JARY(1000),KARY(1000)
            NPAR=0
            BUFFER IN (01,1) (JARY(1),JARY(20))
499         GO TO (500,600,700,800),UNITSTF(01)
500         GO TO 499
700         WRITE(61,701)
701         FORMAT (47H TILT—READLAB HAS ENCOUNTERED EOF AS A LABEL)
            GO TO 9
800         WRITE (61,801)
801         FORMAT (33H READLAB ENCOUNTERED PARITY ERROR)
            NPAR=NPAR+1
            IF (NPAR.EQ.10) 9.10
10          BACKSPACE 01
            GO TO 11
9           REWIND 01
            STOP
600         DECODE (80,2,JARY(1)) NFILE,EVNT,NSTAT,REGN,DATE,TIME,ELAT,ELON,
          1 EMAG,EDINT,EDINQ,DT,CHAN,MMABT
2           FORMAT(1X,I2,1X,2I2,A7,2I8,2F7.1,I4,F4.1,2F4.2,F6.4,I4,I7)
            WRITE(61,3)  EVNT,NSTAT,ELAT,NFILE,ELON,CHAN,REGN,DT,DATE,EDINT,TIM
          1 E,EDINQ,EMAG,MMABT,DEP
3           FORMAT(3X,10HEARTHQUAKE,3X,I2,12X,7HSTATION,3X,I2//3X,3HLAT,3X,F7.
          1 1,14X,4HFILE,4X,I2/3X,3HLON,3X,F7.1,14X,8HCHANNELS,2X,I4/3X,A7,20X
          2 ,8HSAMP INT,2X,F6.4/3X,4HDATE,2X,I8,13X,5HEDINT,3X,F4.2/3X,4HTIME,
          3 2X,I8,13X,5HEDINQ,3X,F4.2/3X,3HMAG,4X,F4.1,16X,13HABS   TIME   MARK,2X
          4 ,I7/3X,5HDEPTH,2X,I4//)
            RETURN
            END
```

Subroutine UNPACK unpacks each consecutive pair of words into four data samples corresponding to the vertical, north, east and time track series.

```
            IDENT             UNPACK
            ENTRY             UNPACK
            COMMON
I1          BSS               1
I2          BSS               1
I3          BSS               1
I4          BSS               1
I5          BSS               1
I6          BSS               1
I7          BSS               1
I8          BSS               1
J1          BSS               1
J2          BSS               1
J3          BSS               1
J4          BSS               1
J5          BSS               1
J6          BSS               1
J7          BSS               1
J8          BSS               1
L1          BSS               1
L2          BSS               1
M1          BSS               1
M2          BSS               1
M3          BSS               1
M4          BSS               1
NZ          BSS               500
NN          BSS               500
```

```
NE          BSS      500
NT          BSS      500
            PRG
UNPACK      UJP      **
            LDA      L1
            SHAQ     -12
            LPA      =O00007777
            STA      M1
            SHAQ     12
            LPA      =O00007777
            STA      M2
            LDA      L2
            SHAQ     -12
            LPA      =O00007777
            STA      M3
            SHAQ     12
            LPA      =O00007777
            STA      M4
            UJP      UNPACK
            END
```