The Caltech Digital Seismograph[1]

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Abstract. A digital data logger has been constructed at the California Institute of Technology for recording the signals from long-period Press-Ewing seismometers. Three-component data are continuously digitized at the rate of 10 samples per second with an 86-db dynamic range and stored on magnetic tape. With a tape speed of 0.5 inch/sec, data for a 24-hour period may be recorded on one 10½-inch reel. An editing system is then used to select interesting events and convert them to a form compatible with the IBM 7090 computer for further reduction and analysis.

Introduction. The techniques of analog recording of seismic information have long been established. More recently, magnetic tape recording has been added to this field (G. H. Sutton and P. W. Pomeroy, private communication, 1962). The significance of the fact that the information can be played back repeatedly for analysis in digital or analog form is well known. Recent work by *Press et al.* [1961] and others has demonstrated the utility of the digital computer in seismic research. The preparation of seismic data from standard chart recordings for use on the digital computer is a cumbersome operation. Clearly, a method of direct digitization and/or preparation of seismic data is necessary.

Several solutions to this problem have been published recently, each solution being tailored to fit a particular need [*Bogert*, 1961; *Haubrich and Iyer*, 1962; *De Bremaecker et al.*, 1962; *Hagelbarger*, 1961]. At the Seismological Laboratory we are engaged in the automatic preparation of seismic information for digital computer reduction and analysis on a scale that to our knowledge has never before been attempted. Our objective is to apply digital data-logging techniques to the field of seismology so as to preserve the greatest spectrum, dynamic range, and sensitivity. The end result is a permanent library tape in 7090 computer format peculiarly suited to direct digital processing.

This paper describes the system approach of the Caltech digital seismograph, without belaboring the reasons for choosing the ultimate methods out of many approaches that might be applicable. Serious consideration was given to economy, reliability, maximum resolution (or minimum noise), and availability of commercial equipment which could be used. Only the digital system, commencing with a voltage from a transducer (seismometer) and ending with the edited digital data of selected events, will be discussed. The seismometer instrumentation and the data reduction subsequent to editing are discussed by *Phinney and Smith* [1963].

Data handling. When considering a general-purpose system like this, one must be aware of the vast amount of data involved. For example, a continuous sampling rate of 10 samples per second produces 864,000 data points per day, per component. For a three-axis system with a dynamic range of 16 bits, this amount of data would fill 30 miles of punched paper tape a day (IBM 7090 format). Actually, many of these data are not needed, for the usual interest is only in specific events. Therefore, a digital seismograph must not only be capable of producing and handling data efficiently but must also contain an editing facility to allow quick access to the interesting events.

The Caltech digital system consists of two separate entities. The first is the digitizing system which continually digitizes the voltage from a seismic transducer. The digital data for a 24-hour period are recorded on 1 reel of magnetic tape. The second is an editing system which incorporates a search routine for locating events

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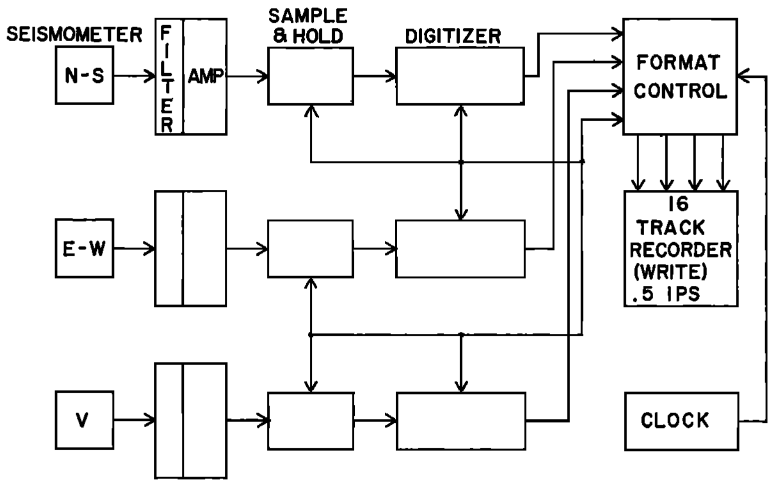


Fig. 1. Block diagram of the digitizing system.

on the tape and rerecording them on a second tape in the 7090 BCD format for further reduction. The two systems are independent of one another to allow simultaneous operation.

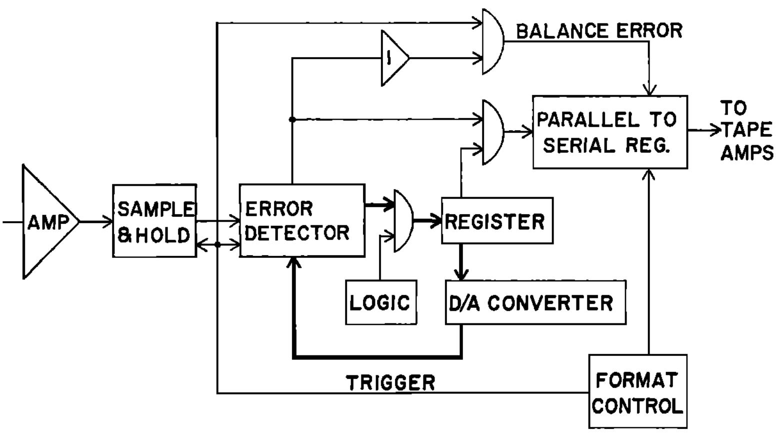
Digitizing system. A block diagram of the digitizing system is shown in Figure 1. Encoding is performed on each individual channel. The digital information is recorded in parallel on a 1-inch, 16-track magnetic tape. Each channel is independent of the others, so that a malfunction in one unit will not affect another. Although three channels are shown, the system may be expanded to six with the addition of amplifiers, sample-and-hold, and digitizers.

Dynamic range and sensitivity are primarily functions of the amplifier, which is a Beckman Fitgo model C-21. It contains a second-order Butterworth low pass filter with a 2-cps bandwidth. The sensitivity is less than 1 microvolt. With the presently used Press-Ewing seismometer with a 500-ohm coil, this corresponds to a ground displacement of 1, 10, and 40mμ at periods of 0.5, 6, and 20 sec. The dynamic range is 86 db. Shortly to be designed are an additional filter to further reduce aliasing and a signal compressor which will extend the dynamic range to 100 db.

The decision to use multiple digitizers as opposed to a single digitizer with a scanner for encoding three or more channels was based upon three considerations. First, a suitable scanner with sufficient dynamic range was not available commercially. Second, the expenditure for three relatively low-speed digitizers is less than that for a single high-speed unit with a scanner. Finally, from a technical viewpoint, the electronic digitizer is a rather complicated instrument and its reliability when operated on a continuous basis was unknown. The repair of a malfunction in a parallel system is considerably easier than in a serial one, and multiple digitizers would minimize system interruption.

The digitizer is an Electro Instrument model 848 that we modified for increased sampling speed. This instrument has a 4-decimal digit range with binary-coded decimal output. Figure 2 is a schematic representation of the encoding process. Essentially it is a double closed-loop process, the heavy black line representing that portion performed by the model 848 digitizer. The purpose of the sample-and-hold, which is of our own design, is to improve the performance of the digitizer and to determine accurately the time of each sample independently of the encoding time.

The encoding process functions in the following manner. Upon command from the format control, the sample-and-hold interrogates the amplifier for a 3-msec interval and then presents a constant voltage to the error detector. This in turn controls a logical procedure (tracking logic) of placing BCD numbers in a register. Each of these numbers is converted to its analog equivalent voltage and compared with the volt-



ENCODING PROCESS

Fig. 2. Block diagram of the encoding process.

age from the sample-and-hold. When a balance is obtained, i.e. when there is no difference, the process stops and a signal is produced by the error detector to indicate that the register contains the present data point. The number is transferred, in parallel, into another register where the format is created before the data point is shifted onto magnetic tape. An external closed loop (light lines, Figure 2) ensures that only legitimate numbers are transferred. If for any reason a balance was not obtained, the number is rejected and an error code is created and recorded.

In such a process, the encoding time is dependent upon the number of logical steps that must be performed to obtain a balance. This in turn is dependent upon the relationship between the present data point and the previous one. In general, the closer the two points, the shorter the balance time. Our modifications of the standard model 848 digitizer have produced average balance times of about 15 msec. Incomplete balances may occur if noise is introduced into the system or if the balance time exceeds the sampling interval because of an excessively large rate of change of the signal. The maximum sampling rate is 20 samples per second for three components or 10 samples per second for six, the limit being determined by the maximum bit-packing density of the magnetic tape recording. At the present time we are operating three components with a sampling rate of 10 samples per second.

Before embarking on the design of such a slow digital tape recording system a study of the problem of intertrack skew at low speed was undertaken. Very few data on intertrack skew for speeds less than the standard 1⅞ inches/sec are available. After having plotted the results of skew tests for tape speeds from 1⅞ to 60 inches/sec and extrapolating the data to ½ inch/sec, it was clear that intertrack skew is inversely proportional to tape speed and becomes increasingly greater as the speed is reduced. At ½ inch/sec the nominal intertrack skew was found to be 1200 microinches per inch. For a 1-inch, 16-channel tape, this would appear to limit the bit-packing density to about 300 bits per inch if each data point is recorded in the conventional way, that is laterally across the tape. However, by recording BCD characters serially in the longitudinal directions, only one-third the width of the tape is involved for each channel and three times the bit-packing density may be accommodated. The present bit-packing density for operating three channels at 10 samples per sec is 200 bits per inch, and no problems due to intertrack skew have been encountered to date. For either 20 samples per sec on three channels or six-channel operation at 10 samples per second, the bit-packing density would be 400 bits per inch, which seems reasonable. The tape transport, Ampex model FR 1100, was modified to transport 1-inch tape at ½ inch/sec. Thus a 10½-inch reel (3600 feet) is sufficient for a 24-hour record of three chan-

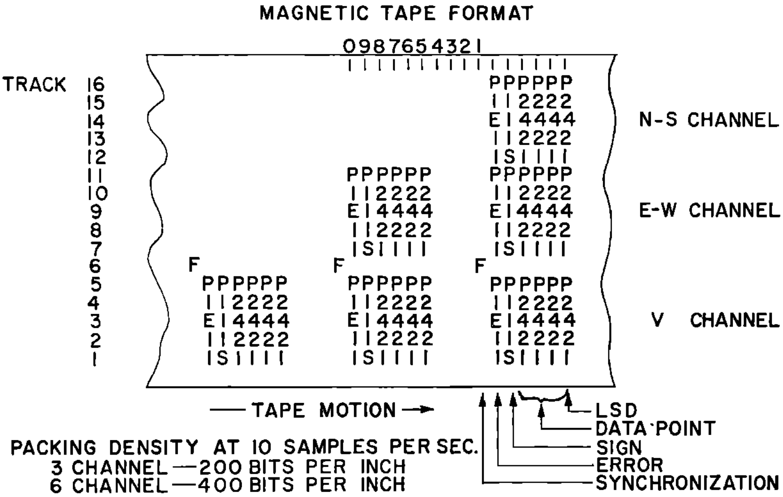


Fig. 3. Magnetic tape format.

nels at 20 samples per second (400 bits per inch per track).

Some concern was expressed over wear of the record head and build-up of oxide from the magnetic tape on the head; the air cushion present at higher tape speeds, which tends to lubricate the head and facilitate the carrying away of oxide, is not present at ½ inch/sec. These fears, it would appear, were unnecessary, for in over 5000 hours of near continuous operation, no noticeable headwear has occurred and the oxide buildup is negligible. In fact, the only oxide produced has been due to rewinding the tape on the machine at very high speed.

The magnetic tape format is shown in Figure 3. Because of the requirement of continuous 24-hour recording, it is not possible to produce a computer tape in 7090 format. The three channels of data are recorded in parallel on a 1-inch, 16-track tape. Each channel has its own odd-one parity, making it necessary to read no more than five tracks in lateral synchronism. As was mentioned earlier, this reduces the intertrack skew by one-third.

The model 848 digitizer, like most digitizers with a large dynamic range (15 bits), produces an output code in binary-coded decimal. Although pure binary is more economical on tape, the conversion from BCD to pure binary is very difficult. Therefore, the machine BCD (2421) is maintained throughout the system and is converted to 7090 BCD format (8421) as the last step in the editing process.

The tape format consists of a 36-bit word with four BCD characters for the data point, one containing the sign bit and one containing a flag bit for indicating a balance error (error flag). In the event of an error flag, the data point produced is −9999. To record the data from six digitizers, the additional words would be recorded alternately between the original ones (increasing the bit-packing density to 400 bits per inch).

Absolute time is not recorded on the tape. The system is controlled by a crystal oscillator having an accuracy of 1 part in 10^6 per day. If the absolute time of the first sample on the tape is known, the time relative to this sample will be known to better than $\pm 1/10$ sec per day. The absolute time of the first sample is obtained by having the start of the digitizing process automatically triggered from our station clock. A very simple time code is then created in the sixth track which contains a file mark used for word synchronization. The time code consists of a bit (time flag) placed in the position adjacent to the file mark, once every 2048 (binary 2^{11}) samples. An event may be found by determining its time relative to the start of the record and counting an appropriate number of time flags from the beginning. In the event of a miscount the resulting error would be a multiple

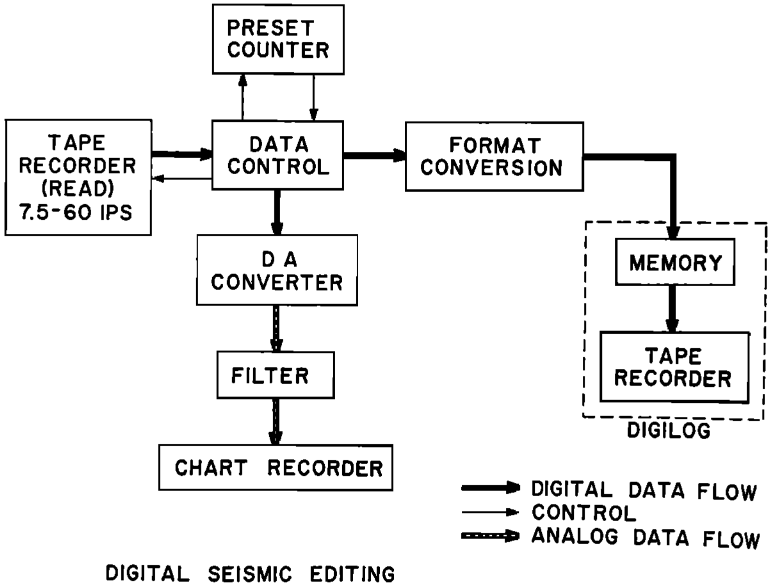


Fig. 4. Block diagram of the editing system.

of 204.8 sec and would be easily discernible in the editing process.

The digitizer is located beside a standard visible drum recording seismograph. The starting time is easily noted by making a circle around the minute mark corresponding to the start of the record.

We have a program for the G15 computer that will perform the computation of the number of time flags, given the Greenwich civil time of the minute mark corresponding to the first sample, the time correction for our station clock (as determined from NPG radio time signal), and the GCT time of the start and end of an event. The computer will determine the number of time flags necessary to find the event (leaving at least 1 minute of background before the start), the number of data samples included in the event, and finally the corrected GCT time for the beginning and end.

Editing system. In the fall of 1963 a 7090–7040 computer facility will be installed at the California Institute of Technology. This system will allow direct data access to the 7040 disk memory. In the interim it is necessary to transfer the raw data from the initial tape to an intermediate IBM tape before final 7090 processing.

A block diagram of the present editing system is shown in Figure 4. The functions of the editing system are to search the tape at high speed, excerpt the interesting events, make a digital-to-analog conversion and a format conversion, and then record the data on a 7090 compatible magnetic tape with record-gap and end-of-file marks.

The editor contains a tape transport which has multiple speed ranges. The tape search is performed by counting time flags, as described earlier, at a tape speed of 60 inches/sec. The predetermined number of time flags are placed in a preset counter which automatically stops the tape unit at the completion of the count. A speed change is made to 7.5 inches/sec, the desired number of data points are placed in the counter, and the data are processed at 15 times real time.

The intermediate tape is created by the Digilog (digital data logger) designed and built by *Kawano and Stiver* [1962] of the Jet Propulsion Laboratory. After format conversion, the data are fed into the Digilog at a continuous 1.5-kc/s character rate. The Digilog fills its buffer memory with 171 data points and then unloads these data onto an IBM magnetic tape with the proper record gap while still accepting new data. Any number of records, up to the capacity

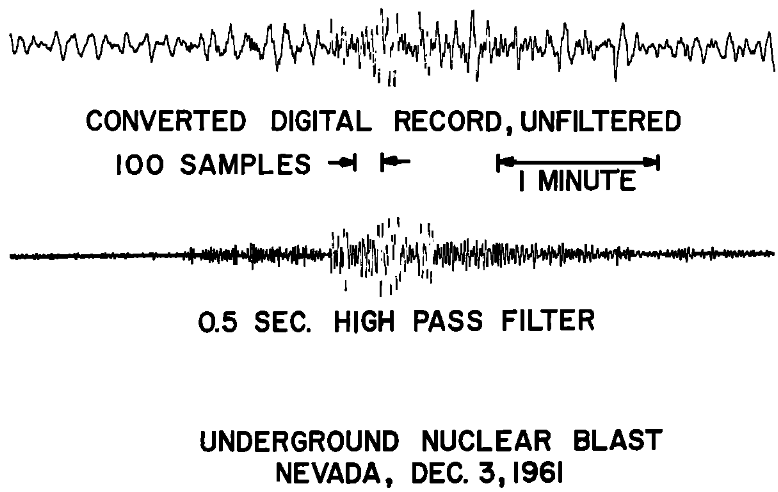


Fig. 5. Example of digital-to-analog converter display, high-pass filter.

of a 10½-inch reel of tape, may be recorded, and at the completion an end-of-file mark will be recorded. After the desired events have been taken from the original tape, it is erased and reused.

To make a visible check of the editing procedure, a digital-to-analog conversion is made and displayed on a dual-channel chart recorder. The dynamic range of the D/A converter is two digits which the operator may select from the four-digit data. The analog data are displayed in two ways. One channel has no frequency compensation other than smoothing to remove the staircase effect produced by the digitization (zero-order hold). This channel represents the full spectrum of the data. With the other channel the operator may select one of two filters or eliminate all filtering. The filters available are a 0.5-sec high pass and a 10-sec low pass (corrected to real time). The proper choice will al-

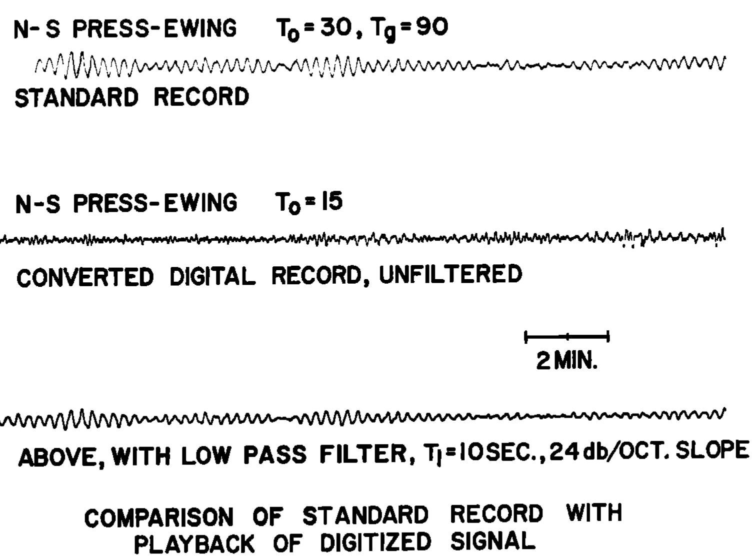


Fig. 6 Digital-to-analog converter display, low-pass filter, and comparison with standard photographic recording.

low the operator to suppress 6-sec microseisms and observe an event which might be buried in the background. An example of a record after the digital-to-analog conversion is shown in Figure 5. Note how the high-pass filter has emphasized the event. In Figure 6 a standard photographic recording is compared with the converted digital record before and after low-pass filtering. If all filtering is switched out, the staircase effect may be observed for checking digitizer operation.

When the 7090–7040 facility is installed an intermediate tape will no longer be required. At the present time each axis is edited separately. We have found that it takes about 1 day of editing for a week's collection of events. With the high-speed data-input capabilities of the 7040 it is planned to serialize the three channels for simultaneous editing and to operate at a 3-kc/s character rate. The subsequent saving will reduce the editing time to 1 or 2 hours a week.

Reliability. In over 6000 hours of nearly continuous operation the reliability of the equipment has been excellent. At this time we have no preventive maintenance program and, except for the occasional replacement of the mechanical choppers in the digitizers (approximately 2000-hour life) and the failure of a fan, a relay, and a transistor, we have had no problems. The tape transports and amplifiers have been trouble free.

The greatest source of system difficulty comes from the problem of compatibility of tapes recorded on one machine which must be played back on a machine of different manufacture. I am referring to the tapes recorded on the Potter transport contained in the Digilog and subsequenty read on the IBM 729 tape unit. Upon the installation of the IBM 7040 computer this problem will no longer exist.

Conclusion. We have learned that reliable 24-hour/day recording of directly digitized data can be accomplished. The problems of high sensitivity, large dynamic range, and reliability are not formidable. The method of digital magnetic recording at slow tape speed is independent of the digitizing process and would seem applicable to a multitude of digital data-logging problems. Finally, from an economic standpoint, if one considers only the data edited up to this writing, the cost per data point is less than that for digitizing conventional records by hand. This cost, of course, will continue to decrease as more data are processed.

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