Some problems of Seismic Data Processing

Part 1. Observational System and Instrumentation

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Abstract

As the first stage of the seismic data processing, the system set up at our Laboratory and Observatory for seismic data collection and processing are described.

In the short-period seismograph system, seismic data are recorded on magnetic tape in analog form and then converted to digital form after selecting the data length and sampling rate. To record only desired data the time-delay equipment with IC-shift registers is adopted. Digitization is carried out by means of a DATAC-1030 digital system.

For the long-period seismograph system, a direct digital recording system is used. The system consists of a 3-component set of long-period seismometers, DC-amplifiers, active RC filter networks, digital voltmeters, and a digital printer with 21 figures. For the triggering circuit the low-pass filtered component from the short-period vertical seismograph is used.

Some examples of records obtained by these systems are shown.

1. Introduction

Though the application of the digital computer, recently remarkably developed, opens a new view for data processing to seismic research, the cardinal task is yet left undeveloped. It is to develop the seismic observational system itself, that is, to make the system adequate to digital analysis. Such research will help ensure the seismic data to have high-fidelity, and thus promote the possibility of new analytical methods, and again a new view on problems of observation and so on will be derived from its result.

From the above point of view, this paper will describe the facilities that have been set up at our Laboratory and Observatory for seismic data collection and processing. For the detailed analysis and automated processing of seismic waves, the first task is to obtain any suitable process of data-digitizing. Generally speaking, there are two ways concerned with the digital data acquisition system. One system is as follows; seismic data are recorded in analog form and events of special interest are converted to digital form after selecting data length and sampling intervals. Digitization of records on photographic or smoked paper is included in this way. The seismic data recorded on analog magnetic tape, recently utilized, are electronically converted to digital form by using a high speed *A–D* converter and stored on digital magnetic tape or punched paper tape[1),2)]. The other system is the direct digital recording system. By the use of this method, it is possible to provide a wide dynamic range and broad frequency band. In addition, this method is a convenient means in computer operations. Several approaches to the problem of direct digital recording system have been published in the last few years[3)-9)].

In the treatment of such events as micro-earthquakes, explosions and volcanic tremors, however, the short-period component plays an important roll and so a sufficiently fine sampling is necessary to obtain the reconstruction of precise waveform. And thus the direct digitizing system requires a great deal of recording medium, that is, magnetic tapes and paper tapes. Then, since the sampling interval and data length corresponding to frequency contents of events can be selected, the former process is preferable for practical use and for lightening the economic burden, unless controlled by a large-scale digital computer.

On the other hand, in the case of recording long-period surface waves and crustal deformations, in which rough sampling intervals, long-time records and wide dynamic ranges are required, the latter system becomes preferable.

In this paper the former system is considered in the first part and the latter is described in the second part.

2. Short Period Seismograph System (Indirect Digitizing System)

2.1 Observation and Recording

The use of magnetic data recorder is nowadays popular in seismic observation, especially for trouble-free, temporary observations. In the case of routine observation, however, if continuous recording is carried out all day, a great number of magnetic tapes will be consumed with the added inconvenience of changing tapes. Furthermore, it is a lengthy and tedious procedure to find the desired event. In order to lighten both the expense and waste of time and labour as much as possible, it is necessary to retain only desired data. Thus, (1) time delay equipment and (2) analytical technique to discriminate seismic signal from background noise should be considered. Wada et al.[10] devised equipment for an automatic seismic recording system with the endless magnetic tape recorder for time-delay and which has been used to observe volcanic earthquakes. The maximum of delayed time of this equipment can be elongated to about 8 minutes in case of the driving tape-speed of $1\frac{7}{8}$ inch/sec. The master store equipment consists of 7 ch PWM type magnetic data recorder. Irikura et al.[11] devised the FM type recording system with magnetic drum recorder for time-delay and obtained the delay time of about 30 sec.

The merit of an endless tape system is in obtaining long delay-time and wide frequency band, but the difficulty of maintenance, especially wear of tape heads, yields considerable disadvantage. On the other hand, the magnetic drum is free from mechanical wear caused from rubbing and tension of tape, but there are also some difficult problems in maintenance, because the equipment must be rigorously isolated from both vibration and shock and the drum housing must be air tight to prevent dust and dirt from abrading the drum surface and heads as the drum rotates. And so its use is restricted to a modern laboratory and is not adequate for usual seismic observation, for example, field observation. Both methods possess merit and demerit, respectively. Then, some new method should be devised. In our observatory the time-delay equipment with IC-shift register has been devised and practically used, as illustrated in Fig. 1.

The sensing instrument is a 3 component set of short period seismometers possessing a natural period of 1.0 sec and damping factor $h=0.64$. The output signal from

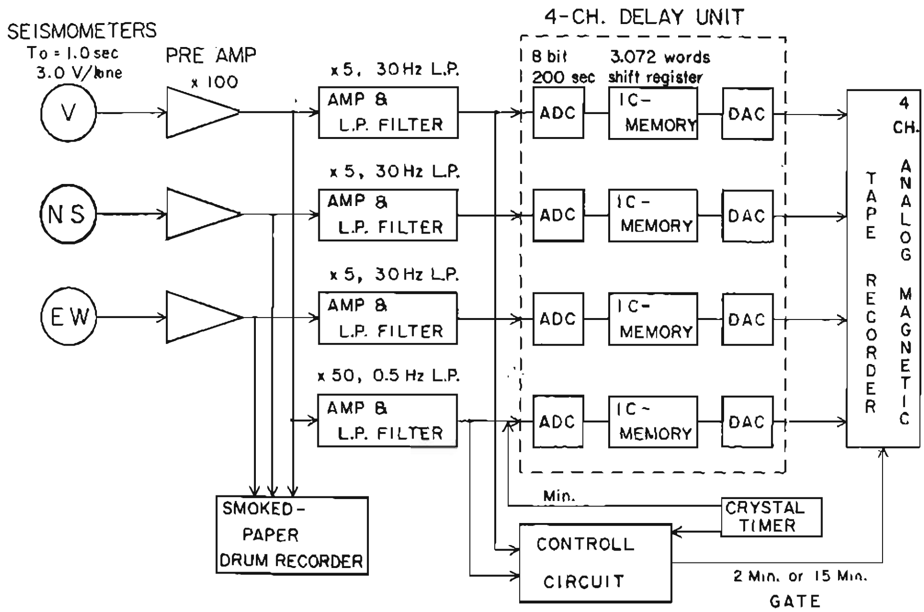


Fig. 1. Block diagram of short-period seismograph system.

each seismometer is connected to a *A–D* converter through a pre-amplifier and a low-pass filter. The low-pass filter is an active RC network filter with a corner at 30 Hz and an attenuation rate of 24 db/oct. The filter output is also recorded on a smoked paper with a drum speed of 60 mm/min. The analog to digital converter is a 8-bit (including sign) successive approximation unit with a dynamic range of ± 5 V. The sampling rate of 200 Hz per second is chosen so that 7 digital data at least would be assured in the case of maximum frequency component of 30 Hz. The digitized data from *A–D* converter are stored in the IC memory which consists of 3,072 8-bit binary shift registers, and so the time-delay of 15.36 seconds is obtainable. The memory output is again converted to analog signals using a *D–A* converter and recorded on standard analog magnetic tape. The delay-time system is controlled by an identical crystal oscillator of 100 kHz, and composed of 4 channels, that is, 3 channels are used as 3-component set consisting of vertical, *N–S*, and *E–W* components and the fourth channel as a vertical component through the low-pass filter with a corner of 0.5 Hz.

To solve the problem of discrimination of seismic signal from background noise, the method of correlogram processing at several observational points is used with considerably high reliability in seismic array system[12]. In recording at one station, however, there is no useful method except for examining amplitude level. In this case the arrival of a seismic wave is decided when the amplitude exceeds an assigned value. The effectiveness of this method is strongly influenced by the noise level at the station.

At Amagase station, the background noise of the vertical component is predominant between 1 and 5 Hz, though the general noise level is low. And so, for local earthquakes the trigger level of the starter is set to be operated for the frequency component beyond 10 Hz and for farther earthquakes, below 0.5 Hz.

Operational duration of storing recorder is activated for 2 minutes when the triggering is caused by some high frequency component, and for 15 minutes when the triggering is caused by some low frequency component. It is noticed that the low-frequency component is also used for the starter of the recording system of long-period seismic waves, as will be mentioned. Fig. 2 shows two examples of records obtained by this system.

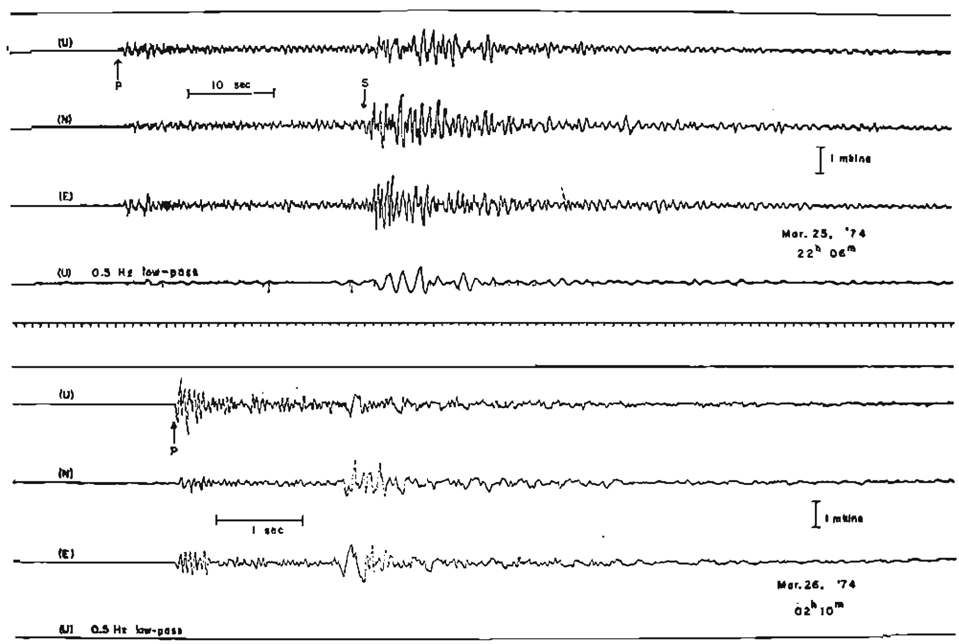


Fig. 2. Examples of records: upper; $t_{S-P}=28.7$ sec, lower; $t_{S-P}=1.88$ sec.

2.2 Digitization

The analog data recorded on magnetic tape are converted to digital form through the high speed *A–D* converter. Its sampling frequency, f, should be usually determined to be so high as to prevent any noise, usually of appreciably high frequency, from being aliased across the folding frequency, $f/2$. The sampling rate determined for this procedure becomes often high beyond that determined on normally analysing the phenomena if neglecting noise, that is to say, this would mean tedious procedure and preparation of a great deal of memory capacity. In practice, therefore, the high frequency components should be preliminarily eliminated by a suitable low-pass filter, considering magnitude and epicentral distance of each event. Thus the practically effective sampling rate may be determined and applied to the seismic data of interest.

The actual value of sampling interval is as follows; in the case of near-distance event ($S–P<10$ sec), 0.01 sec per each channel through the low-pass filter with the corner frequency of 25 Hz and the attenuation rate of 30 db/oct, and in the case of farther-distance event (S–P > 10 sec), 0.02, 0.04 and 0.10 sec, empirically chosen from examining the wave form, are usually used through the low-pass filter with the adequate corner frequency corresponding to each sampling interval. Furthermore, for the convenience of the particle motion studies, band-pass filtered data in some frequency ranges are also digitized.

The *A*–*D* converter used for digitization is a DATAC–1030 digital system, as described by Yoshikawa et al.[2] This equipment has the following main abilities: the input range is from +9.99 to −9.99 V; the number of channels is three; the maximum sampling rate is 3,000/sec in the case of use of one channel; if an external oscillator is applied for generating the clock pulse, arbitrary sampling rate below 3,000/sec is available. The digitized BCD output is once recorded on magnetic tape and then punched out on paper tape at the maximum speed of 110 characters/sec.

2.3 Computer Operations (Editing, DA conversion and Particle Motions)

After being edited on the computer with regard to data length and data format, data in digital form is stored on the library magnetic tape. The index files of library tape that consist of source parameters, site condition, classification of filter, sampling interval, and so on are stored on disk pack and are easily referenced by utilizing the searching routine program as previously prepared. An example of typical listing of index files is shown in Fig. 3.

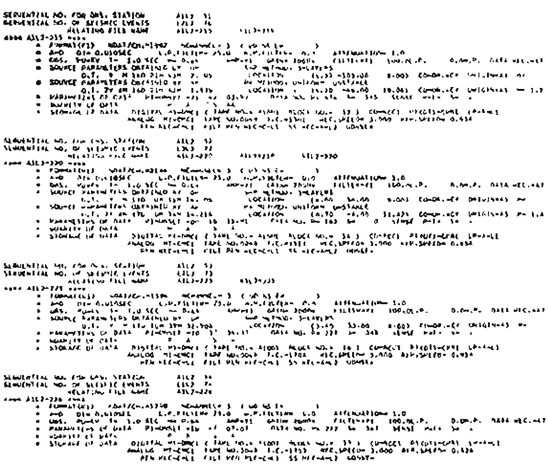


Fig. 3. A typical listing of index file.

The data on the tape are displayed on a X–Y plotter or printed out by line-printer, and are examined to check error and any overloading in encoding process from analog to digital. The *D*–*A* records of 25 Hz low-pass and six band-pass filtered data are shown in Fig. 4 for comparison.

Particle motion studies have been serving as a routine criterion in picking and identification of phases, and up to this time have been made by many investigators who have manually read photographic records and plotted the results. The recent development of the digital system enable us easily to produce a set of particle motions on a X–Y plotter for desired frequency bands, covering an arbitrary interval of an entire seismogram. In Fig. 5 P and S type motions of the event shown in Fig. 4 both in the horizontal and vertical planes are shown.

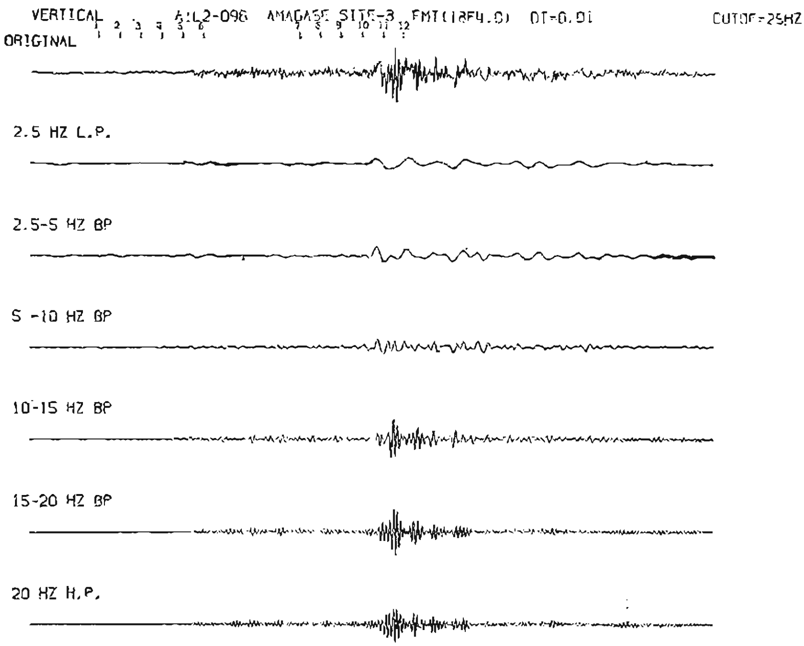


Fig. 4. Example of D–A records on X–Y plotter. Top trace represents 25 Hz low-pass data, and the other six traces show the band-pass filtered data.

3. Direct Digital System

3.1 Digital Long-Period Seismograph System

The most standard system for a long-period seismograph is an optical recording system utilizing a long-period galvanometer. Since the long-period galvanometer is very fragile and subject to drift for several reasons (charges on their terminals, thermal convection, etc.), it is not always easy to obtain reliable data. And when the analog seismograms from a drum-recording system are digitized, errors may occur due to misalignment of the digitizer relative to the galvanometer swing and the results obtained by certain kinds of digital analysis will be errorneous[13].

Considering these problems, several systems for a long-period seismograph have been studied[3)-9),14)-16)] The high gain and wide band electromagnetic seismograph for long-period range devised by Pomeroy et al.[14] is based on use of a photo-tube amplifier connected to a galvanometer. Though this system is well conceived, the difficulty of galvanometric recording is left untouched.

The merits of galvanometer recording are in operating below the microvolt level and also in acting as a effective low-pass or band-pass filter[15]. Since the sensitivity

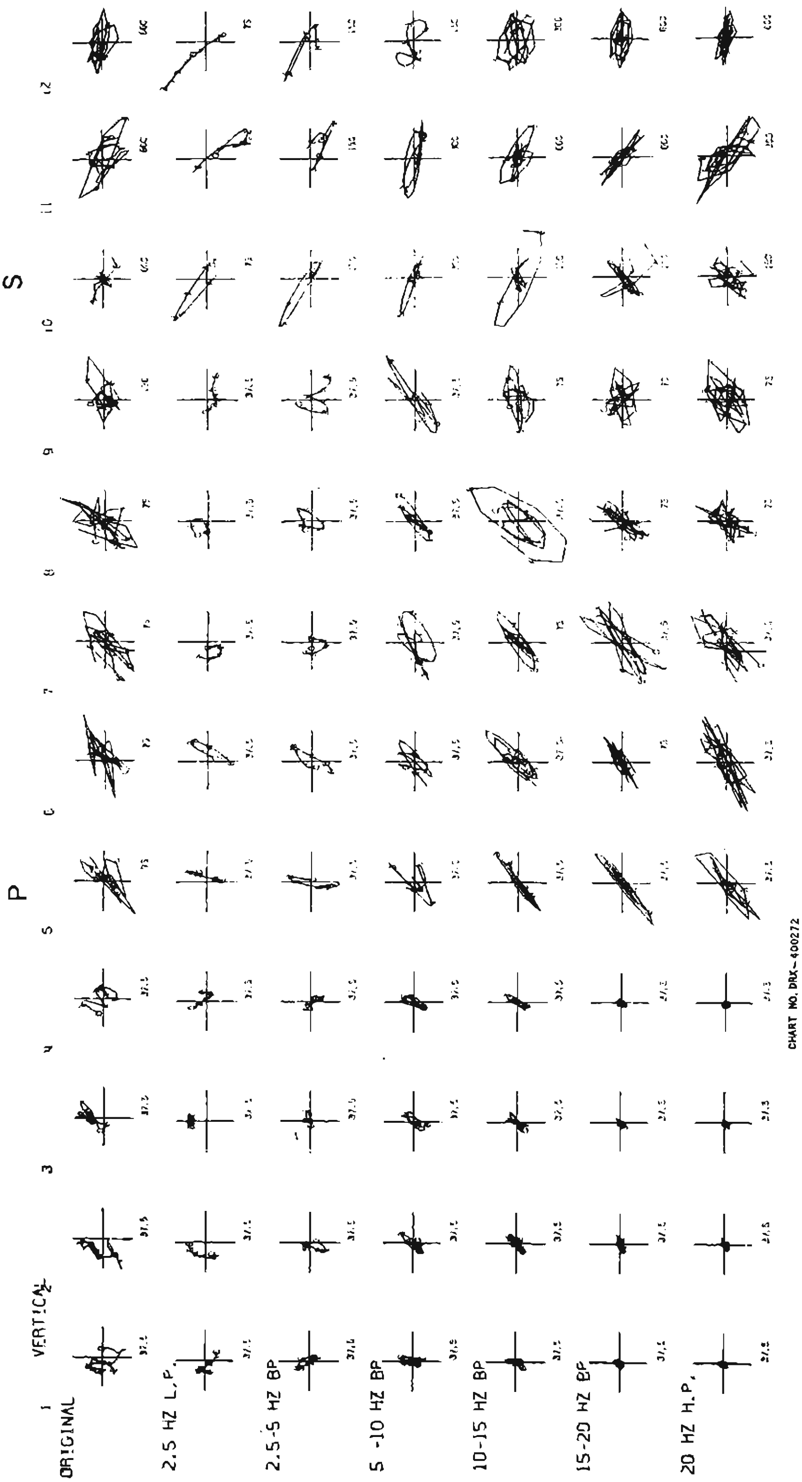
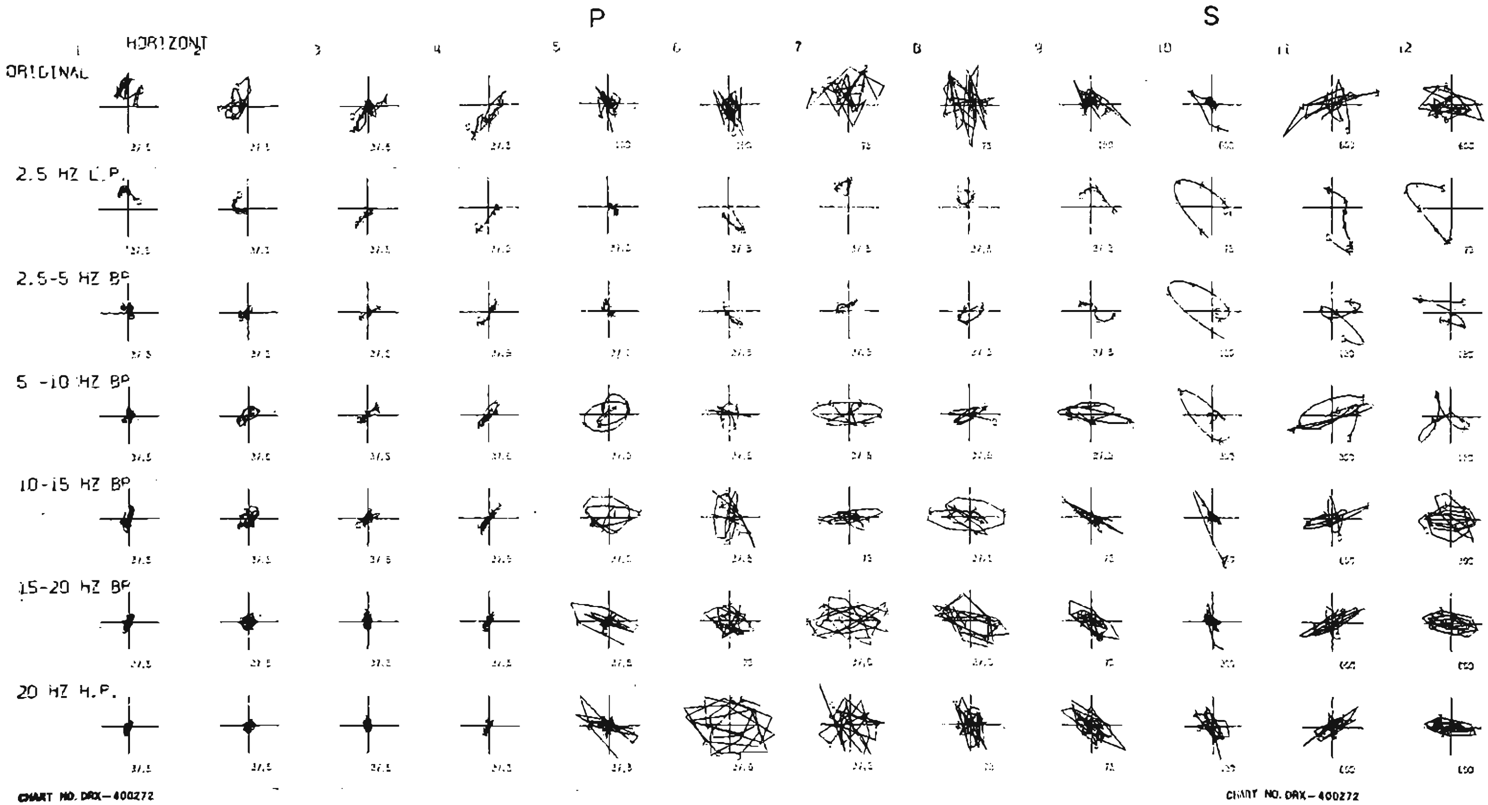

P
S
ORIGINAL
2.5 HZ L.P.
2.5-5 HZ BP
5 -10 HZ BP
10-15 HZ BP
15-20 HZ BP
20 HZ H.P.
VERTICAL
CHART NO. DRX-400272

Fig. 5 (a)



(b)

Fig. 5. Particle motions of *P* and *S* type motions, (a); in the vertical plane (b); in the horizontal plane, for 0.64 sec interval. The number of intervals corresponds to that of Fig. 4.

of long-period seismograph systems, in practice, must be restricted by the background level of the microseisms in the period range of 4 to 9 seconds, the amplitude in this period range must be reduced. It becomes particularly important in direct digital recording system to be free from aliasing and to minimize the data as much as possible. Thus, in the long-period seismograph system without using the galvanometer it is necessary to device a low-pass filter for cutting off the characteristic period range of microseisms with a precise high-gain DC amplifier for amplifying the seismic signals. Such systems generally are accepted by several investigators[3)-5),7)8)16)].

As another device, De Bremaecker et al.[9)] present a direct digitizing seismograph based on a displacement transducer. In their system a high voltage level is applied to improve the amplifying operation, and a feed-back circuit is applied to minimize long-term drift. Taking account of the unstability of the electric power source and the humidity in our observatory, the system using an external power source and a capacitance type transducer is not adequate to our system, and the passive RC networks require a large capacitance, usually not available without concern for dielectric leakage and unstability of characteristic constant. Therefore, a system with the DC-amplifier and active RC filter networks of a low-noise operational amplifier is thought to be adequate to our purpose.

In a study of long-period seismic waves it should be noticed that amplitude of surface waves is often greater than the amplitude of body waves, and also the ratio of amplitudes is high. And so a wide dynamic range is necessary for recording system. The maximum dynamic range obtained by an analog recorder is at most not beyond 50 db. On the other hand, in the use of a direct digitizing system, it is not difficult to obtain a dynamic range greater than 60 db. As the sampling rate of 10 per second may be enough for long-period seismic waves, the design of an A–D converter becomes technically easy and economically feasible. Therefore, the use of a direct digital system becomes more effective than the system of two steps, analog recording and then digitizing.

The digital long-period seismograph system set at the Amagase Observatory is described below.

3.1.1 The Amagase digital seismograph system

The block diagram is shown in Fig. 6. The seismometer pendulum is a 3 component set of long-period Press-Ewing type pendulums. The free period is set to be 20 seconds. The geographic coordinates of site are 34°52′48″N and 135°50′09″E. The site is located at 500 m from the entrance of the tunnel and at depth of 140 m.

The output signal from each moving coil (15,000 turns, 30 kΩ) is fed to a 3 channel chopper-stabilized operational amplifier which has a voltage gain of 10^2, and also acts as an active low-pass filter with a corner at 0.1 Hz and an attenuation rate of 6 db/oct. The input impeadance of the amplifier is 50 kΩ in accordance with critical damping resistance. The signal from each amplifier is connected to a second stage DC amplifier through an active low-pass filter (0.02 Hz, -12 db/oct). Fig. 7 shows the frequency response of first stage amplifier, low-pass filter and overall systems, respectively. The output is converted to digital form by a five place digital voltmeter (DVM) which consists of a integrating PWM analog-digital converter. Since the range of the DVM is ± 1.1000 V, the least significant digit represents

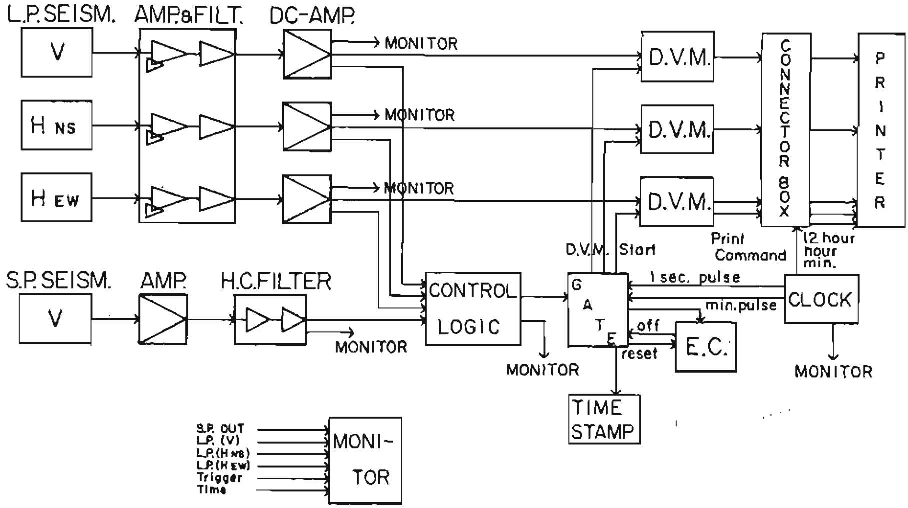


Fig. 6. Block diagram of the Amagase long-period system.

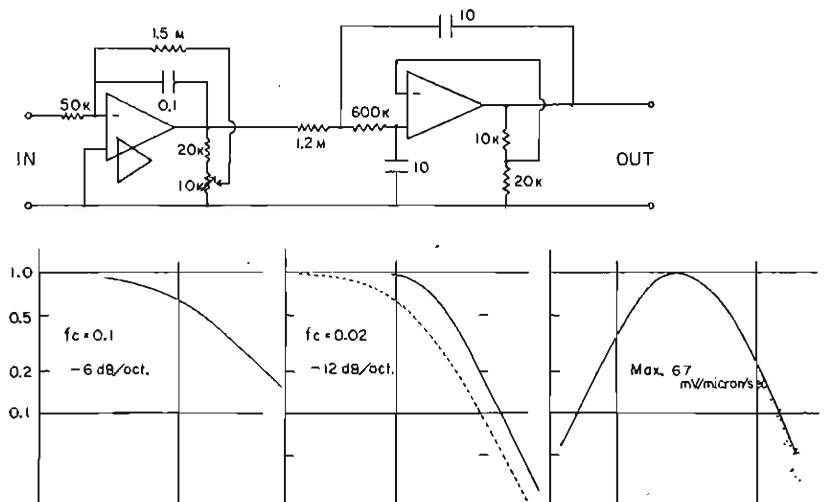


Fig. 7. Upper part; amplifier and filter circuit.
Lower part: freuqency response of first stage amp., low-pass filter, and overrall system. Dotted line represents frequency response of a conventional 100 sec galvanometer.

0.1 mV. The sampling rate is 1 per second. Encoding is performed on each individual channel by an identical crystal timer and each channel is independent of the others.

To store the data in digital form, a digital magnetic tape is most desirable, but it is considerably expensive and an editing device must be added to provide the format for computer analysis. Moreover, the recording on punched paper tape is not always adequate to long-term routine operation, as seen from the machine mechanism of a tele-printer. Considering these, a digital printer with 21 figures is adopted for printed output record. Since the amounts of recording data are limited by paper length, only the desired data intervals must be printed out. Hence the printer is devised to be operated only when the amplitude of seismic waves exceeds an assigned level. As the initial motion of long-period *P* waves is generally small, it is not easy to detect the arrival of this motion. It is also very difficult to expect the use of delay-time equipment, because both the very long delay-time and the great dynamic range are indispensable. Therefore, the low-passed vertical component from short-period system, as described in 2.1, is applied to drive a starter. Using this triggering device the printer can be started to operate at a time from 2 to about 60 seconds after arrival of *P* initial motion.

To determine the practical set of operational duration after triggering, it must be noticed that a near event without a long-period component could trigger and be recorded, and to avoid this undesired state of affair the normal duration of recording is assigned to be 30 minutes. And if any long-period component, desired phase is triggered, the duration is reset and elongated to 120 minutes. In the case of very distant earthquakes, usually very small component of short period, the gate is adjusted to be opened also when two components of long-period system exceed a trigger level at the same time. So, surface waves with large amplitude may be obtained. Fig. 8 shows the controlled circuit and the time chart. This instrument spends usually one roll to record 4–5 events and has a time stamp to print the triggering time.

The scratch type strip-film recorder is also used, and the 3-channel records of the outputs from second stage DC-amplifiers in analog form and the 2-channel records, the low-passed short-period vertical component and the triggering pulse, are recorded.

Finally the data obtained in this system are punched manually on cards and processed by computer as well as in the case of the short period system.

3.2 Examples of Records

Observation using this system has been carried out since June, 1973. The trigger level was at first set at 300 mV (ground velocity; 450 μkine) in long-period components considering high noise level and zero drift of amplifier and at 200 mV (140 μkine) in short-period component. By applying this level it was possible to obtain the seismic waves from the earthquakes of magnitude beyond 4.5 near Japan, 5~5.5 for teleseismic distance, and 6 for much farther, respectively. As a result of technical improvement of electronic circuit, the reduction of drift of amplifier and long-period noise enabled the trigger level to be assigned to 100 mV since Dec., 1973.

Figs. 9–12 show some examples of the records of earthquake obtained by the analog recorder. In the figures the top and bottom trace show the time mark (minutes) and the other traces show the record of low-pass filtered short-period vertical component, the long-period vertical, *N–S*, and *E–W* components, and the trigger pulse from the top, respectively. Fig. 9 shows the earthquake near Choshi (Δ=450 km, M=5.6). The digital record is triggered at 11 seconds later than short-period initial motion because of the very small *P* initial wave. Here the long-period *P* wave which

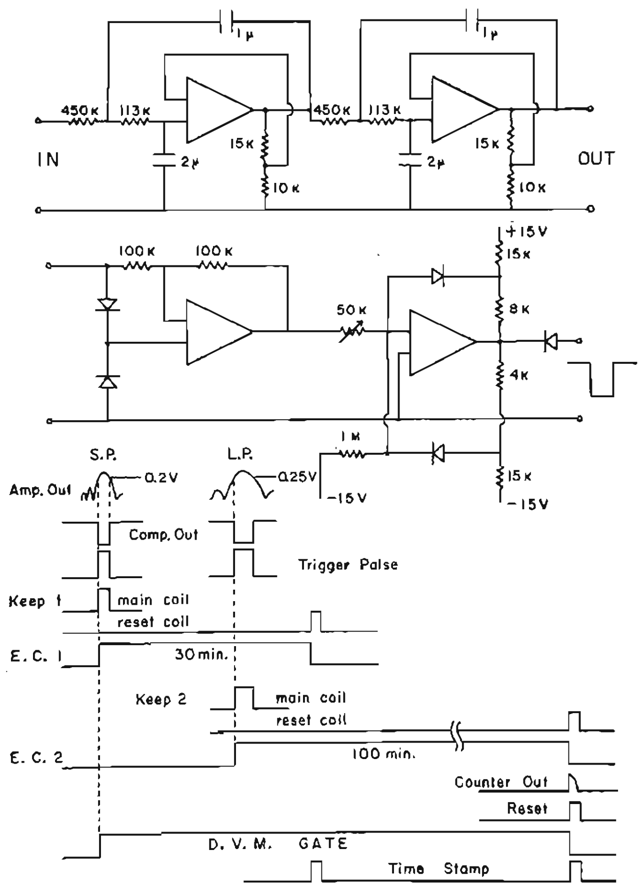


Fig. 8. Triggering circuit and time chart of the control system.

appears before S wave arrival may be noticed.

Fig. 10 and 11 show the records of the Philippine earthquake of July 6, 1973, (M=5.6, Δ=2650 km) and the Aleutian earthquake of Nov. 7, 1973, (M=5.9, $\Delta \approx$4200 km), respectively. As seen from both records, the P phases of the events are predominant in short-period component but not in long-period component. Thus the duration of initial portion missed is not beyond several seconds. The saturated parts in the figures are owing to the narrow dynamic range of the recorder (maximum $\pm$0.4 V). As an example of digital records, the D–A converted wave forms transformed to radial and transverse components, and the particle motions in vertical and horizontal planes of these two earthquakes are shown in Fig. 13 and 14.

Fig. 12 shows the China earthquake of Aug. 11, 1973, (M=5.4, Δ=2938 km). In comparison with the Philippine earthquake in Fig. 10, though the magnitude and epicentral distance do not differ so much, the amplitudes of body waves, especially short-period components, are small, but the amplitudes of surface waves are comparable. That is, this example shows that the AND circuit of two long-period components used as the trigger circuit is not sensitive for Love waves from the western

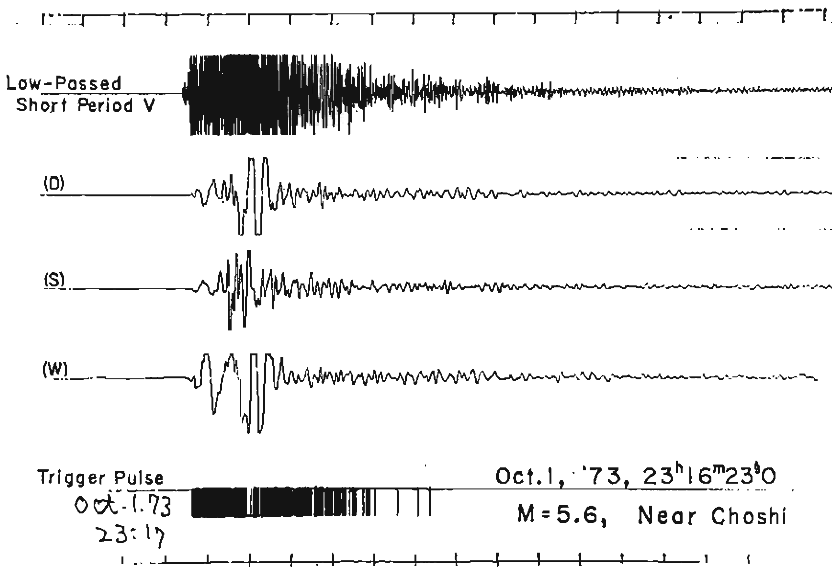


Fig. 9. Analog recor of earthquake of near Choshi, Oct. 1, 1973. $\Delta = 450$ km, $M=6.5$.

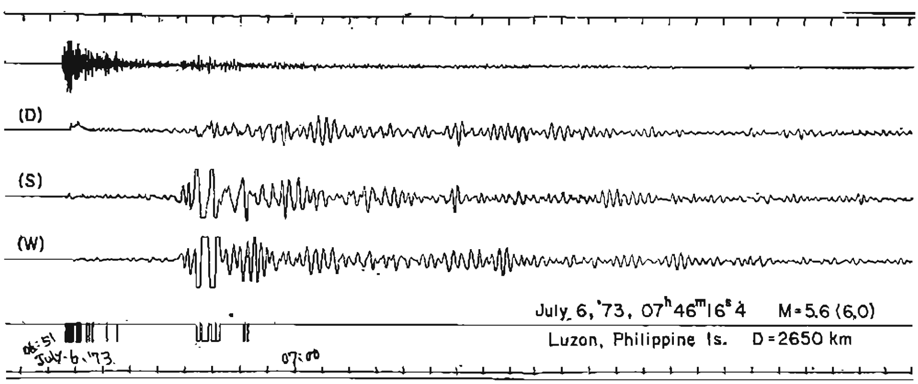


Fig. 10. Analog revord of the earthquake of Philippine, July 6, 1973, $07^h46^m16^s.4$, $\Delta = 2650$ km, $M=5.6$.

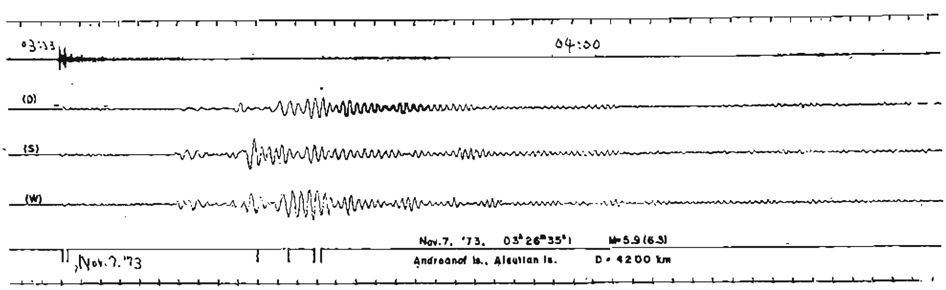


Fig. 11. Analog record of the earthquake of Aleutian Is., Nov. 7, 1973, $03^h26^m35^s.1$, $\Delta \approx 4200$ km. $M=5.9$.

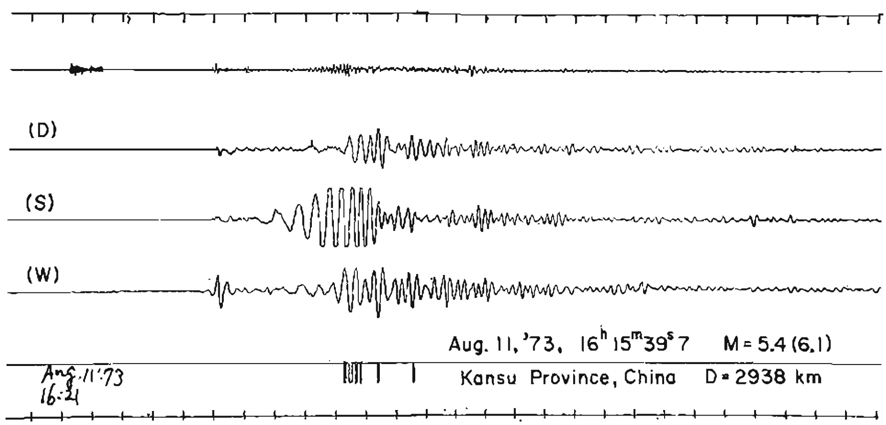


Fig. 12. Analog revord of the earthquake of China, Aug. 11, 1973, $16^h 15^m 39^s 7$, $\Delta = 2939$ km, $M = 5.4$.

direction such as this earthquake. Therefore, the digital system was operated at 9 minutes after *P* initial motion.

3.3 Direct Digital Recording of Extensometer

All systems described above are concerned with the digitization of analog output from the seismograph. There is another way to obtain directly as a discrete digital quantity without recording as an analog quantity. As an example of this method, the observational system of crustal deformation detected by the extensometer is shortly described here. The detail of the system has been described in another paper[17]. This method is also similar to that of the long-period seismograph system provided by Aki et al.[6] in which a short-period galvanometer as the sampling device of the deflection of recording galvanometer have been used.

The recording of extensometer has usually been based on the optical method. Since the crustal deformation is very slow phenomenon, such slow sampling as 1 per minute is sufficient to reproduce the record. So the following photo-electric converter was designed. Two photo-cells aligned vertically are devised to be translated at speed of 9 mm/sec on the driving shaft by a synchronous motor. The lower photo-cell receives the light beam from the lamp used for the base line and generates one pulse which acts as the start signal of counter. The upper photo-cell receives the light beam from extensometer mirror and generates another pulse as the stop signal. In such a way the deflection of extensometer is converted into time interval between two pulses, which is measured by a universal counter. The output from a counter is punched out on the paper tape or printed out on the recording paper. At the same time the output is converted back to analog form and recorded by chart recorder. The block diagram and time chart of this system is shown in Fig. 15. This system is adequate to long-term continuously recording of a slowly changing quantity.

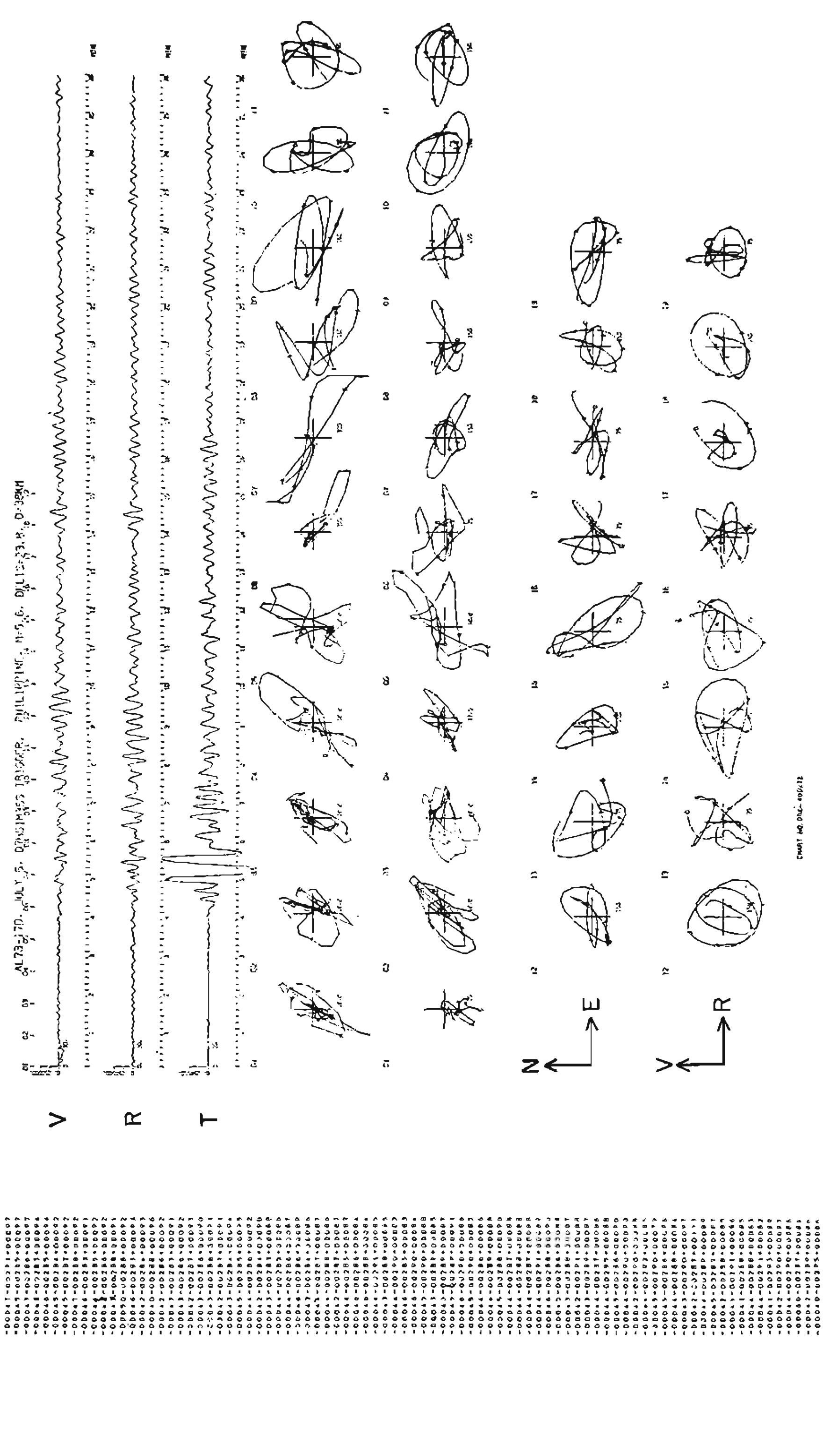


Fig. 13. Digital revord, *D–A* converted waveform, and particle motions of the earthquake of Fig. 10.

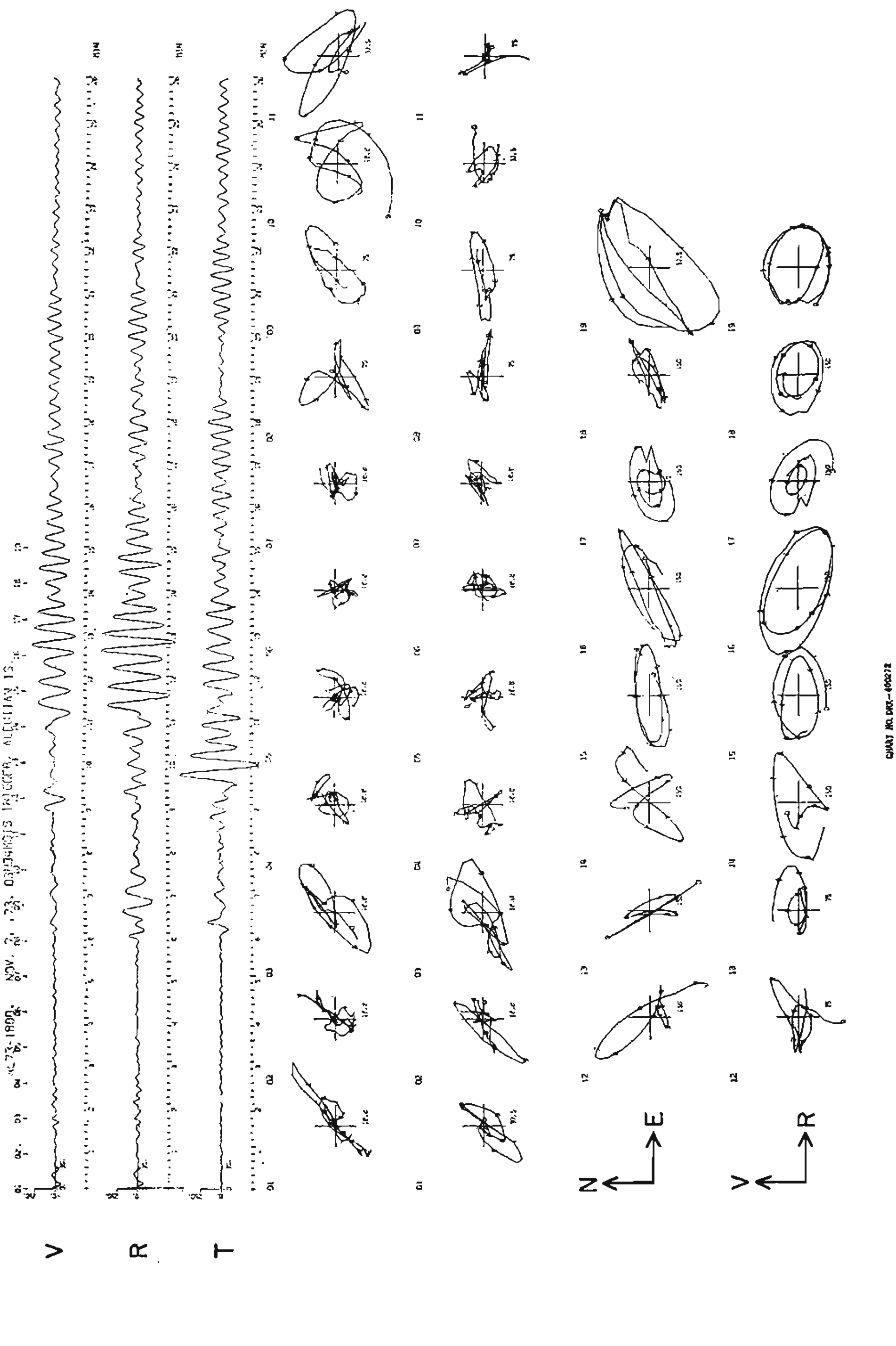


Fig. 14. *D–A* converted waveform and particle motions of the earthquake of Fig. 11.

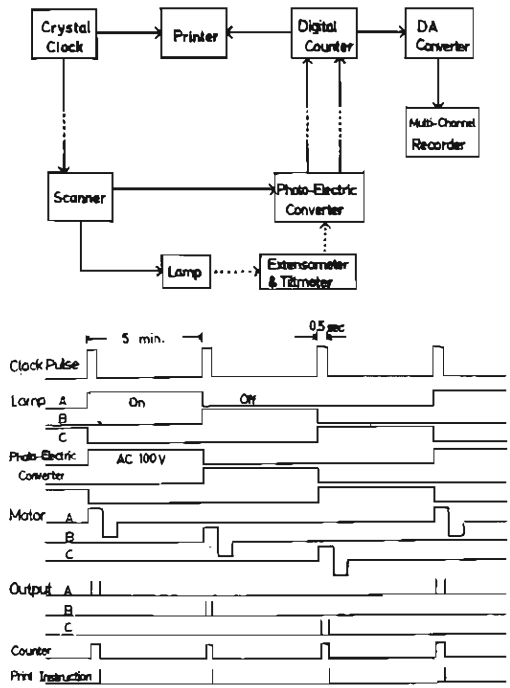


Fig. 15. Block diagram and time chart of recording system of extensometer.

4. Conclusion

The data collection system to obtain digital records set up at the Amagase Crustal Movement Observatory have been described. Principal effort was made to operate continuously for routine observation and to keep the cost of the equipment as low as possible. Some difficult problems are to file a great deal of data as compactly as possible, and to establish the automatic data processing systems. If such a processing system could be established, it would be possible to use the digital magnetic tape for the storing equipment of a long-period seismograph system. It is a more important problem to design the starting control devices by which the arrival of a seismic wave can be decided precisely. It is necessary to solve this problem for the development of an observational system, especially a long-period system, but it may be impossible unless effective methods of discrimination are studied.

Moreover, there is the problem of improvement of the seismometer, not yet treated in the system described here. In future, a new system including the transducer must be designed. In long-period seismograph the adjustment of environmental conditions also becomes an important factor for stable operation of system.

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References

1) Bogert, B. P.: Seismic data collection, reduction, and digitization, Bull. Seism. Soc. Am., Vol. 51, 1961, pp. 515–525.
2) Yoshikawa, S., T. Wada, and T. Furuzawa: Application of analog-digital converter for seismic data, Special Contr. Geophys. Inst., Kyoto Univ., No. 4, 1964, pp. 105–110.
3) Miller, W. F.: The Caltech digital seismograph, J. Geophys. Res., Vol. 68, 1963, pp. 841–847.
4) Phinney, R. A. and S. W. Smith: Processing of seismic data from an automatic digital recorder, Bull. Seism. Soc. Am., Vol. 53, 1963, pp. 549–562.
5) Smith, S. W.: Seismic digital data acquisition systems, Rev. Geophys., Vol. 3, 1965, pp. 151–156.
6) Aki, K., H. Matsumoto, M. Tsujiura, and T. Maruyama: A digital, telerecorded, long-period seismograph system, Bull. Earthq. Res. Inst., Vol. 43, 1965, pp. 381–397.
7) Haubrich, R. A. and H. M. Iyer: A digital seismograph system for measuring earth noise, Bull. Seism. Soc. Am., Vol. 52, 1962, pp. 87–93.
8) Burke, M. D., E. R. Kanasewich, J. D. Malinsky, and J. F. Montalbetti: A wide-band digital seismograph system, Bull. Seism. Soc. Am., Vol. 60, 1970, pp. 1417–1426.
9) De Bremaecker, J. Cl., P. Donoho, and J. G. Michel: A direct digitizing seismograph, Bull. Seism. Soc. Am., Vol. 52, 1962, pp. 661–672.
10) Wada, T. and K. Kamo: An equipment for a automatically seismic recording, Annuals Disast. Prev. Res. Inst., Kyoto Univ., Vol. 13A, 1970, pp. 35–40.
11) Irikura, K. and J. Akamatsu: Earthquake motions observed on ground and rock, in preparation.
12) Birtill, J. W. and F. E. Whiteway: The application of phased arrays to the analysis of seismic body waves, Phil. Trans. Roy. Soc., London A, Vol. 258, 1965, pp. 421–493.
13) Jaines, D. E. and A. T. Linde: A source of major error in the digital analysis of world wide standard station seismograms, Bull. Seism. Soc. Am., Vol. 61, 1971, pp. 723–728.
14) Pomeroy, P. W., G. Hade, J. Savino, and R. Chander: Preliminary results from high-gain wide-band long-period electromagnetic seismograph systems, J. Geophys. Res., Vol. 74, 1969, pp. 3295–3298.
15) Pomeroy, P. W. and G. H. Sutton: The use of galvanometers as band-rejection filters in electromagnetic seismograph, Bull. Seism. Soc. Am., Vol. 50, 1960, pp. 135–151.
16) Benioff, H.: Long-period seismograph, Bull. Seism. Soc. Am., Vol. 50 1960, pp. 1–13.
17) Furuzawa, T., K. Onoue and M. Takada: On the digital observation of crustal deformation by means of extensometers with photoelectric recorder, J. Geodetic Soc. Japan, Vol. 19, 1973, pp. 76–84.