BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 43 (1965), pp. 381-397

24. *A Digital, Tele-recorded, Long-Period Seismograph System.*

By Keiiti AKI, Hideteru MATUMOTO, Masaru TSUJIURA
and Takuo MARUYAMA,

Earthquake Research Institute.

(Read Dec. 22, 1964.—Received March 31, 1965.)

Introduction

By the use of a digital seismograph,[1),2),3),4),5)] we obtain not only extreme convenience for computer analysis of seismic waves but also much higher accuracy in sampling interval and in sampled values than by the cumbersome manual reading of chart recordings. The design of a digital seismograph depends on the purpose of research. For example, the Caltech digital seismograph[6)] was designed to attain the greatest spectrum, dynamic range and sensitivity ever obtained by a single seismograph. Their sampling rate is 10 per sec, the dynamic range is 86 *db*, and the recording is made on a magnetic tape. Thus one hour recording of 3 components seismograph produces 108,000 samples. The computer time expended in the analysis of this amount of data must be considerable, even if a large-scale digital computer is used.

We limit our purpose to the analysis of long-period seismic waves in a period range from 10 to 300 seconds. Our sampling rate is 1/2 per sec, the dynamic range is 59 *db*, and the recording is made by punching on paper tape. In order to prevent "aliasing", waves with shorter periods than 4 seconds are suppressed before the sampling by the use of standard pendulum-galvanometer combination. For the present, only the vertical component seismograph is used and the one hour recording produces 1800 samples. This amount of data can be easily processed by a middle-sized digital computer.

---

1) B. P. BOGERT, *Bull. Seis. Soc. Amer.*, **51** (1961), 515-525.

2) R. A. HAUBRICH and H. M. IYER, *Bull. Seis. Soc. Amer.*, **52** (1962), 87-93.

3) J. Cl. De BREMAECKER, P. DONOHO and J. G. MICHEL, *Bull. Seis. Soc. Amer.*, **52** (1962), 661-672.

4) W. F. MILLER, *J. Geophys. Res.*, **68** (1963), 841-847.

5) R. A. PHINNEY and S. W. SMITH, *Bull. Seis. Soc. Amer.*, **53** (1963), 549-562.

6) *loc. cit.*, 4).

The seismograph is set at a new vault built in the yard of the Tsukuba branch station of the Earthquake Research Institute located at a distance of 60 km from Tokyo. The pendulum period of the seismograph is 15 seconds, and its moving coil output is connected to a 90-sec galvanometer. The deflection of galvanometer mirror is pulse-position-modulated by a photo-electric device, and sent to the receiving station at our Institute building, Hongo, Tokyo by a radio-telemetering system. At the receiving station, the signal is converted to 3 decimal digits and punched on paper tape.

For the convenience of checking the operation of the system, the digitized signals are converted back to analog form and recorded continuously on a chart recorder.

Principle of digitizing device

There is a well known problem of "aliasing"[7] in equally spaced sampling. Suppose we want to obtain the power spectrum of seismic waves. If the sampling interval is Δt, then the power spectrum $P_a(f)$ (aliased spectrum) computed from the samples is related to the true spectrum $P(f)$ by the following formula,

$$P_a(f) = P(f) + \sum_{n=1}^{\infty} P\left(\frac{n}{\Delta t} + f\right) + \sum_{n=1}^{\infty} P\left(\frac{n}{\Delta t} - f\right) .$$

If $P(f)$ vanishes for $f \geq 1/2\Delta t$, then $P_a(f)$ is identical to $P(f)$ for $1/2\Delta t \geq f \geq 0$, and there is no problem of aliasing. Otherwise, the aliased spectrum involves contributions from the frequencies $n/\Delta t + f$ and $n/\Delta t - f$ $(n = 1, 2, \cdots)$.

As mentioned in the introduction, we are only interested in the period range 10 to 300 sec. If the continuous signal to be digitized involves no power for the periods shorter than 10 sec, then we are, in principle, able to compute the true spectrum for $T > 10$ sec, by sampling at 5 sec intervals. But, in practice, the signal always contains some power for the periods shorter than 10 sec. Since the smaller sampling rate economizes the computer time in data processing, we want to make the rate as small as possible. For this, we must suppress the short-priod signals before digitizing. There are several ways to do this suppression, but we adopted a long-period galvanometer for this device, because this is the

7) R. B. BLACKMAN and J. W. TUKEY, *Measurement of Power Spectra* (New-York, 1958), p. 31.

standard and well establised device in seismology, its advantages as well as its limitations being well known.

As pointed out by De Bremaecker et al.,[8] the long-period galvanometer is poor in versality and ruggedness, and the drift is always a problem. However, it is also true that if carefully operated, the galvanometer recording can furnish seismologists with reliable data. Moreover, the problem of aliasing will be very serious if we use the direct digitizing seismograph proposed by De Bremaecker et. al. instead of galvanometer recording seismograph. As shown in Fig. 3 of their paper, the magnification of the direct digitizing seismograph is 20 to 30 *db* greater than that of the Press-Ewing seismograph for periods of 1 to 10 sec, if the magnification for periods longer than 20 sec is made nearly the same. This means that the aliasing from these periods is also 20 to 30 *db* greater in the direct digitizing seismograph than the Press-Ewing. We shall show that the former seismograph is not adequate for our purpose.

For a proper choice of sampling rate, it is necessary to know the true spectrum of seismic waves. The variability of the spectrum is very large. It depends on the wave type (body wave or surface wave), epicentral distance, focal depth, magnitude of source and many other factors. However, it is generally accepted that the spectrum is nearly flat if we take the velocity of ground motion as the signal. In fact, Kanai[9),10)] found that the spectrum of ground motion velocity is nearly flat if the effect of the superficial soft layer is neglected. It is also our general experience that the records obtained by a displacement seismograph show the prevalence of long-period oscillation, the records by an accelerometer show the prevalence of short-period oscillation, and the records by a velocity-meter look mostly whitened.

For a rough estimation of aliasing effect, we shall assume that the spectrum of ground velocity due to an earthquake is flat. Then, the greatest aliasing effect will come from the frequency $1/\Delta t - f$. Using the magnification curve given by De Bremaecker et al., we can calculate the value of $P(1/\Delta t - f)/P(f)$ for the direct digitizing seismograph and the Press-Ewing. The value for $f = 0.05\, c/s$ ($T = 20$ sec) is $-3\, db$ for the former and $-17\, db$ for the latter, if the sampling interval Δt is 5 sec. Since this value is too large even for the Press-Ewing, we took the

8) *loc. cit.*, 3)

9) K. KANAI, *Bull. Earthq. Res. Inst.*, **39** (1961), 85-96.

10) K. KANAI, S. YOSHIZAWA and T. SUZUKI, *Bull. Earthq. Res. Inst.*, **41** (1963), 261-270.

sampling interval of 2 sec. For $\Delta t = 2$ sec, the aliasing effect is $-11\,db$ for the direct digitizing seismograph, and $-32\,db$ for the Press-Ewing. We regard this latter value as being satisfactory, and adopt the sampling interval of 2 sec. The practical device for sampling the galvanometer deflection will be described later.

Vault

The geographic coordinates of the seismograph vault are 36°12′38″N and 140°06′35″E. The vault was built on a sloped hill-side close to the main building of the Tsukuba branch station. At the vault site, weathered granitic rocks are removed to depths from 1 to 5 meters, and a $4.5\,m \times 9\,m$ building was built. This building is of reinforced concrete and consists of three rooms; a seismometer room, a galvanometer room and a room for electronic equipment. The first two rooms are covered with soil of thickness up to $3\,m$ as shown in Figs. 1, 2 and 3. The seismometer pier $2.7\,m \times 1.2\,m$ is isolated from the floor of the building.

Fig. 1. Basement of the seismograph vault.

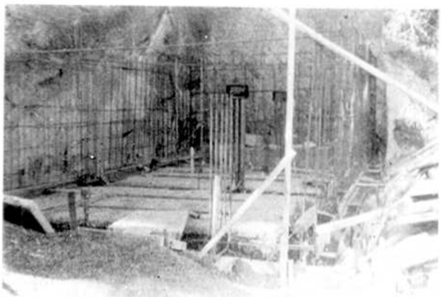


Fig. 2. Vault under construction.

Fig. 3. External appearance of the vault. The seismograph and galvanometer rooms are covered by soil.

A dehumidifier is operated in the galvanometer room. The temperature in the galvanometer room is kept constant by the use of a mercury thermo-switch and heaters. They also control the humidity and temperature in the seismograph room through a hole in the wall between the two rooms.

Seismogragh

The seismometer pendulum is of the LaCoste type, and is manufactured at the machine shop of our Institute.[11] The construction of the pendulum is similar to that of the Press-Ewing seismograph except that our pendulum mass is about 2/5 of theirs. A stable operation is possible up to a period of 40 sec, but, for the present, the period is set at 15 sec.

The moving coil output of the seismometer is connected to a 90 sec galvanometer through an attenuater. This galvanometer is a product of the Physical and Chemical Research Institute, Tokyo. The suspension strip is made of phosphorous bronze instead of gold used in the Lehner galvanometer.

As will be shown later, our seismograph works as satisfactorily as the Press-Ewing seismograph. This comparison was possible because 3 components Press-Ewing type seismographs have been operated at Tsukuba as a part of the IGY program of the Lamont Geological Observatory since 1958.

Sampling device

The sampling of the deflection of recording galvanometer is made by the use of a short-period galvanometer which sweeps a light beam at the sampling time. Fig. 4 shows this devive schematically. L_s is the source of light beam, G_s is the sweeping galvanometer which is driven by a sawtoothed current, and M is a cylindrical mirror which sends the light beam from the mirror of G_s back to that of the recording galvanometer G_p. The first photo-cell R_1 receives the light beam from G_s and the second one R_2 receives it from G_p.

As Fig. 5 illustrates, the deflection of recording galvanometer G_p is converted into time interval between two pulses generated by the passage of light beam across R_1 and R_2. The width of the saw-tooth is 0.1 sec, and the interval between successive saw-teeth is 2 seconds. The

11) K. AKI and S. ANDO, reported at the spring meeting of the Seismological Society of Japan, 1962.

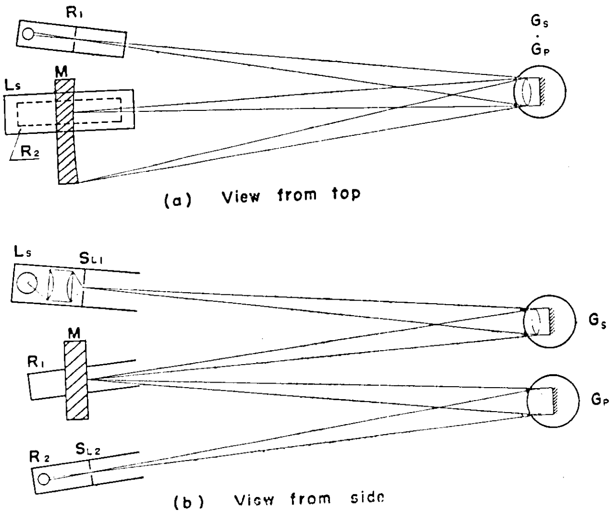


Fig. 4. Schematic view of the photo-electric sampling device.

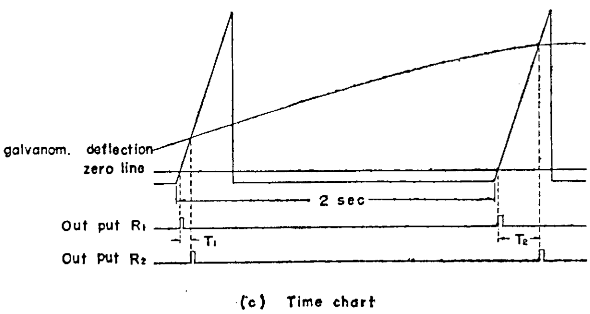


Fig. 5. Time chart of the photo-electric sampling device.

sweeping galvanometer has the natural period of 0.01 sec, and damped critically by means of viscous silicon oil. The linearity of the saw-toothed shape was found satisfactory as will be shown later. The triggering of saw-toothed current is controlled by a crystal oscillater with a time precision of 5×10^{-5}.

Digital recording

The signals are sent from Tsukuba to Tokyo by a UHF telemetering system constructed by Miyamura and Tsujiura.[12),13)] The carrier frequency

12) S. MIYAMURA and M. TSUJIURA, *Bull. Earthq. Res. Inst.*, **35** (1957), 381-394.
13) M. TSUJIURA and S. MIYAMURA, *Bull. Earthq. Res. Inst.*, **37** (1959), 193-206.

is 417.7 *Mc/s*, and 7 subcarriers are provided to send 7 independent signals. For the present, one of the subcarriers (16 *kc/s*) is modulated by the pulse from the photo-cell R_1 and another (19 *kc/s*) by the pulse from R_2 in a manner described later in the section of error check.

At the receiving station in Tokyo, the pluses are reproduced and control the gate between a 10 *kc/s* pulse generater and a decimal 3 digits counter, that is, the pulse from R_1 opens the gate and that from R_2 closes the gate. The time interval between the two pulses ranges from 0.01 to 0.1 sec (the lower limit being imposed because of the space between the photo-cell R_1 and the cylindrical mirror M) and the counter produces numbers from 100 up to 999.

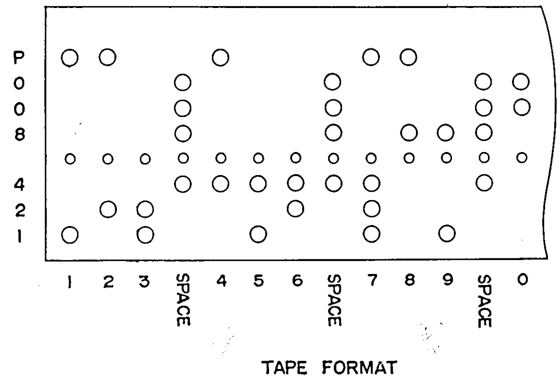


Fig. 6. The format of digital tape.

These numbers are punched on a paper tape in a BCD format (1248) as shown in Fig. 6. Space marks are inserted between the successive data. This format is compatible with the OKITAC 5090 computer at the Computing Center, University of Tokyo.

Analog recording

The first two digits of the digital data are converted back to analog form and recorded continuously by a chart recorder. This recorder has the paper speed of 15 mm/min and registers minite and hour marks. The last digit was omitted for economical reason, but we found that the recording of the first 2 digits is satisfactory for the purpose of checking operation of the digital seismograph.

Fig. 7 shows the photograph of the digital and analog recorder.

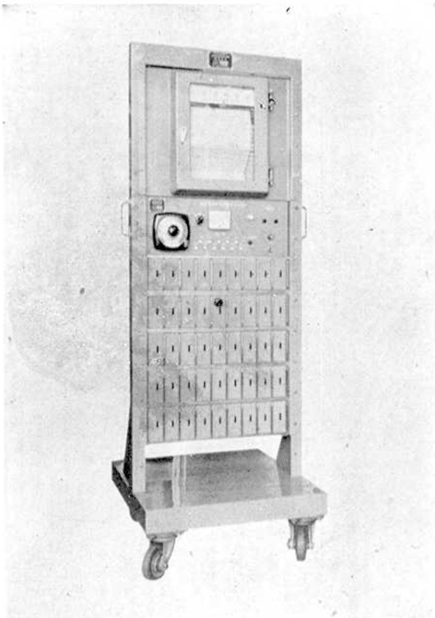


Fig. 7. The appearance of the analog and digital recorder at the receiving station.

Timing and starter device

Although the analog recorder works continuously all the time, the punching of digital data does not occur until significant seismic waves are present. This device tremendously economizes the time for editing digital tape. The punching is triggered either when the amplitude of digital signal exceeds an assigned value or when the amplitude of signal from another seismograph[14] with peak response around 1 sec, which is also telemetered from Tsukuba and recorded on a helical drum, exceeds an assigned value. Once triggered, the puncher works for a time which can be assigned up to 3.5 hours. This use of trigger is justified because we are primarily interested in surface waves. Besides, when the short-period seismograph works satisfactorily as a starter, we only miss the first 2 seconds of P waves.

Although the analog recorder furnishes us with the absolute times, it is difficult to find accurately the time when the first punch occurred from this recorder because of its low paper speed. Therefore, we superpose the instants of punching on the records of the starter seismograph which has a paper speed of 60 mm/min. Once the first punch time is determined, the time of any sample on the digital tape can be found from the number of preceding space marks. The accuracy of time interval between space marks is 5×10^{-5}, which is sufficient for our purpose. A device is provided to produce a blank on the punched tape between two successive events.

Error check and correction

Sources of errors may be classified into 1) photo-electric sampling device, 2) radio telemetering, 3) counter and 4) punching machanism.

14) S. MIYAMURA and M. TSUJIURA, *Special Bull. Earthq. Res. Inst.*, No. 8 (1964).

1). At first, it was a worry whether the sweeping galvanometer which oscillates in a saw-toothed form every two seconds could stand a long term operation. But, a proper operation has been maintained for more than a year without any special care. The errors in the sampling device have primarly come from noises in the circuit which converts light signal into electric pulse. In order to minimize these noises, the output of the photo-cell is put into an amplitude discriminater, differentiated and enters into a flip-flop circuit. Also, between the photo-cell and the discriminater a gate was provided which opens only in the sampling time (during which the saw-tooth sweep is made).

2). In order to gain in the S/N ratio in the transmission line, we adopt the frequency shift method. That is, the subcarrier of 16 kc is sent at a constant amplitude during the time from the onset of pulse from the photo-cell R_1 to the onset of pulse from R_2 and the subcarrier of 19 kc is sent also at a constant amplitude in the other times.

3). When an error is detected on the analog recorder at the receiving station, we examine the filter outputs of the two subcarriers on an oscillo-scope. If they are proper signals, the source of error is in the counter circuit. The error in this part is usualy caused by mal-actions of *AND* and *OR* gates due to circuit noise, insufficient pulse height, and circuit instability.

4). The error in punching may not be detected on the analog record, because the $D-A$ conversion is made before the punching. However, the error occurring in this part is of a simple kind and can be easily detected and corrected in the following correcting process.

The correction of error in the obtained digital data is made by the use of the OKI-typer which can read, type and re-punch the data from tape and also type and punch the data from keyboard. If an erroneous value is found in the original tape, we replace it, in the reproduced tape, with a value interpolated from the values at neighbouring points.

Calibration

Calibration of the seismograph was made by the Fourier analysis of its response to a step function current applied to an auxiliary coil attached to the pendulum mass.[15] Fig. 8 shows computer plots of our digital records by the application of the current (*plus step*) and by its removal

15) A. F. Espinosa, G. H. Sutton and H. J. Miller, *Bull. Seis. Soc. Amer.*, **52** (1962), 767–779.

(*minus step*). The sampling time interval is 2 seconds. This method gives a satisfactory result for periods greater than about 15 sec (which we are concerned with). It must be noted, however that this method is not satisfactory for shorter periods than 15 sec because the amplitude response decreases with decreasing period and at 15 sec it is as small as one hundredth of that at 200 sec and may easily be distorted by the background microseisms such as noticed in Fig. 8.

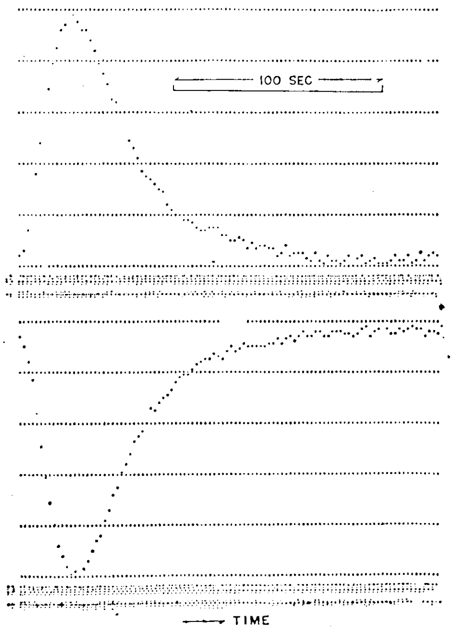


Fig. 8. Computer plot of the digital tape output due to plus and minus step currents applied to an auxilliary coil.

We measured three pairs of responses, each on different microseismic conditions, and computed Fourier amplitude and phase spectra. The discrepancy of the amplitude and phase spectra between different measurements is less than 2% for periods greater than 40 sec and about 4% at 20 sec. Those for *plus step* agree with those for *minus step* within the same range of error. This indicates satisfactory linearity of the saw-tooth motion of the sampling light beam, because if it is not linear, the plus and minus step current will produce response with different magnitude and shape.

The step function current applied to coil is equivalent to the ground motion of the form of 3 times integrated δ-function. Since the seismograph responses are usually given relative to the ground displacement, we multiply the measured amplitude response by f^3 and subtract $3\pi/2$ from the measured phase delay. Table 1 shows the resultant response obtained from the average of three pairs of measurements. The amplitude is given in an arbitrary scale, and the phase is given in parts of a circle. For the present, the absolute amplification is set about 5 counts per micron at 20 sec.

Example of records

Fig. 9 shows the record of the New Britain earthquake of Nov. 18, 1964, (M=6.1) obtained by the analog recorder. Since, as mentioned before, only the first two digits are converted to analog form, the record is not smooth. However, for the purpose of checking the operation of digital seismograph this recording is satisfactory. In Fig. 9, this record is compared with the one obtained by the Press-Ewing seismograph (T_0=15 sec, T_g=90 sec, V_{max}=750) located at about 50 meters from our

Table 1. Magnification and Phase Delay Relative to the Ground Displacement

Frequency (c/s)	Period (sec)	Magnification	Phase delay (parts of a circle)
0.002	500	5.6	−0.630
0.004	250	36	−0.586
0.006	167	93	−0.535
0.008	125	180	−0.484
0.010	100	280	−0.430
0.012	83.3	390	−0.385
0.014	71.4	490	−0.346
0.016	62.5	590	−0.312
0.018	55.6	690	−0.277
0.020	50.0	760	−0.248
0.022	45.5	825	−0.223
0.024	41.7	870	−0.205
0.026	38.5	905	−0.186
0.028	35.7	935	−0.168
0.030	33.3	955	−0.152
0.032	31.3	970	−0.138
0.034	29.4	980	−0.126
0.036	27.8	985	−0.116
0.038	26.3	985	−0.108
0.040	25.0	990	−0.100
0.042	23.8	990	−0.090
0.044	22.7	980	−0.082
0.046	21.7	975	−0.075
0.048	20.8	970	−0.068
0.050	20.0	965	−0.062
0.052	19.2	955	−0.056
0.054	18.5	950	−0.048
0.056	17.9	940	−0.043
0.058	17.2	930	−0.037
0.060	16.7	920	−0.032
0.062	16.1	910	−0.026
0.064	15.6	900	−0.021

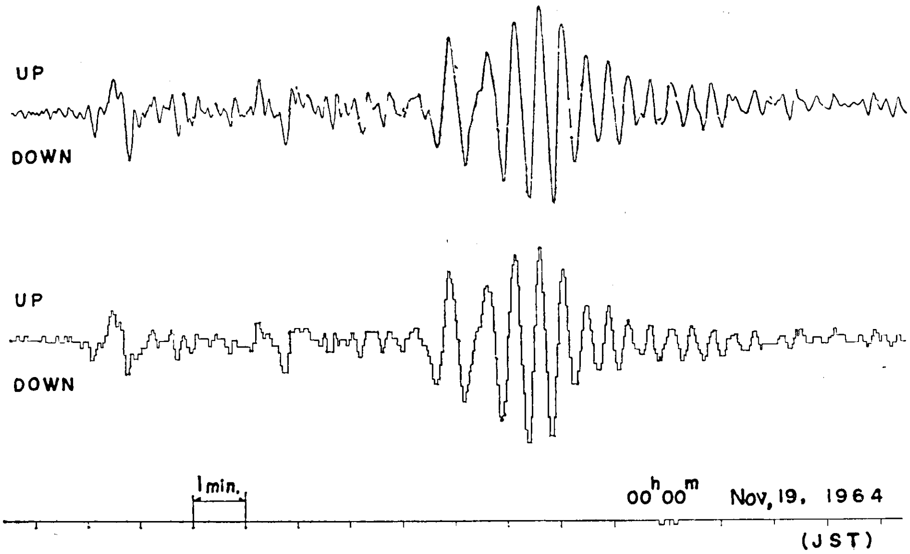


Fig. 9. Comparison of the records obtained by a Press-Ewing type seismograph and by our analog recorder (the first two digits are continuously converted into analog form). Both seismographs are located at Tsukuba.

seismograph vault. The comparison shows that the two seismographs register nearly identical seismograms except that the Press-Ewing is slightly more sensitive to short-period waves. This small difference is caused by the difference in pendulum and galvanometer damping. Fig. 10 shows the computer plot of the digital data for the same earthquake.

Routine analysis of digital data

When an event is recorded by the digital seismograph, we process

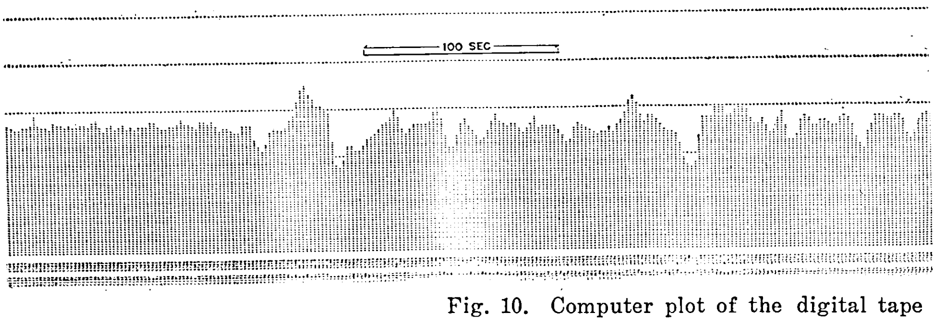


Fig. 10. Computer plot of the digital tape

the data in the following way.

1) The absolute time of the first punch is read from the starter seismogram, and marked on the tape.

2) The portion of the tape which contains significant seismic signals is chosen with the aid of the analog record, and, copied, by the use of the OKI-typer, on another tape to be used for computer analysis.

3) If an error is found, it is corrected at this stage.

4) The edited tape is sent to the Computing Centre, University of Tokyo, and the content is plotted by the OKITAC 5090. Examples of the output sheet are shown in Fig. 10. The serial number and data value are also typed out for each data point.

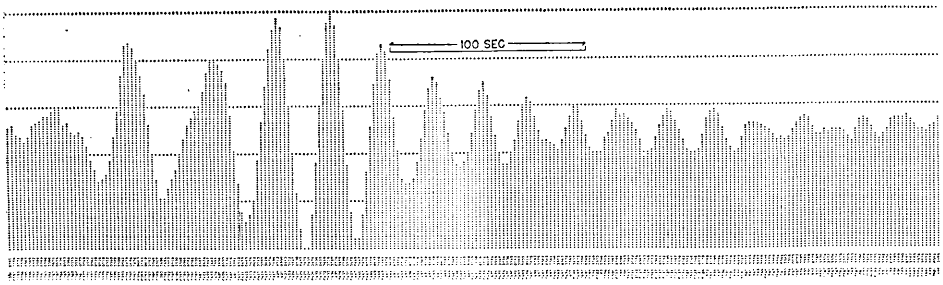
5) From this plot-out, we determine the serial numbers corresponding to the beginning and the end of the Rayleigh wave portion. If other distinct waves of some interest are found, the corresponding serial numbers are also determined.

6) The edited tape is again sent to the Computing Centre for the Fourier analysis of selected wave portions. The output of this analysis includes the amplitude $|A(\omega)|$, phase delay $-\phi(\omega)$ and group delay $-d\phi/d\omega$ spectra, where the wave portion $f(t)$ is expressed as

$$f(t)=\frac{1}{\pi}\int_0^\infty |A(\omega)| \cos(\omega t+\phi(\omega))d\omega ,$$

t being measured from the first data point of the wave portion. Fig. 11 shows these spectra for the Rayleigh waves (R_2 and R_3) from the Ceram Sea earthquake of Jan. 24, 1965.

The above processing is applied to every event satisfactorily recorded by the digital seismograph. Thus, our digital library stores (1) original digital tape, (2) analog record, (3) edited digital tape, (4) computer plot-



for the same event as shown in Fig. 9.

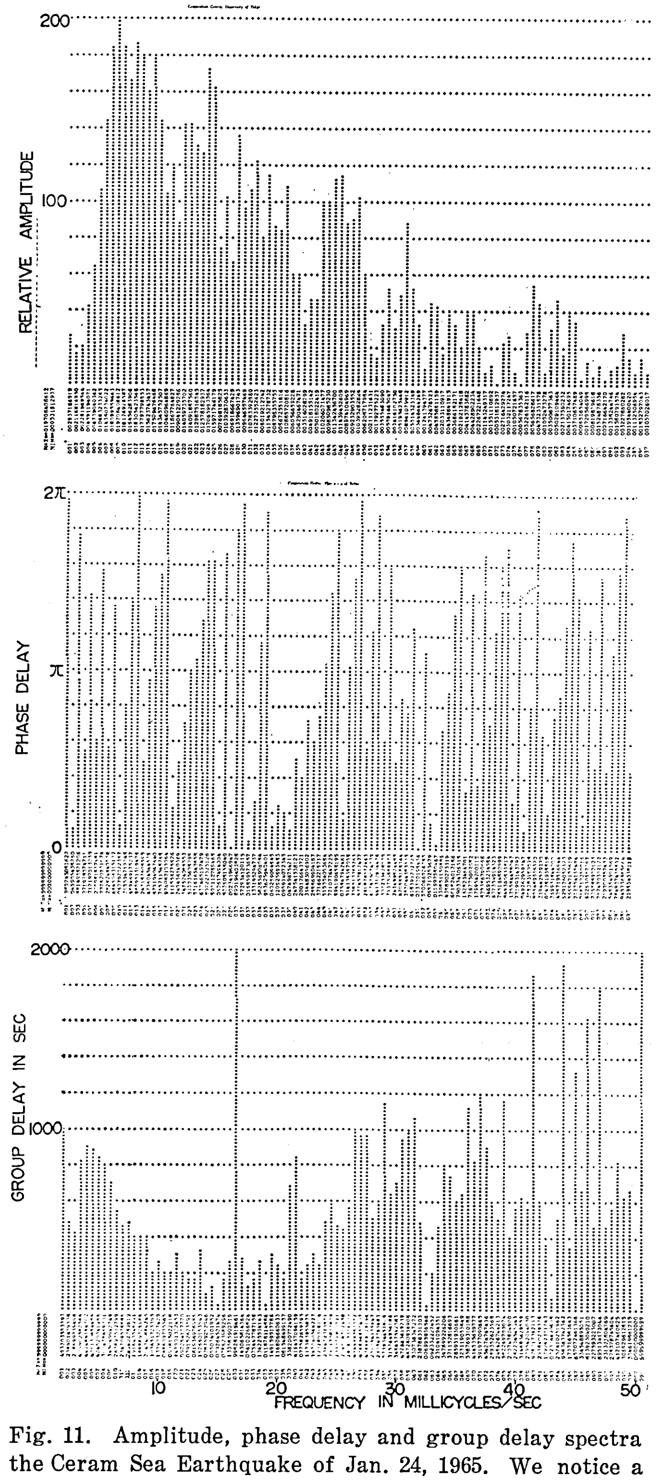
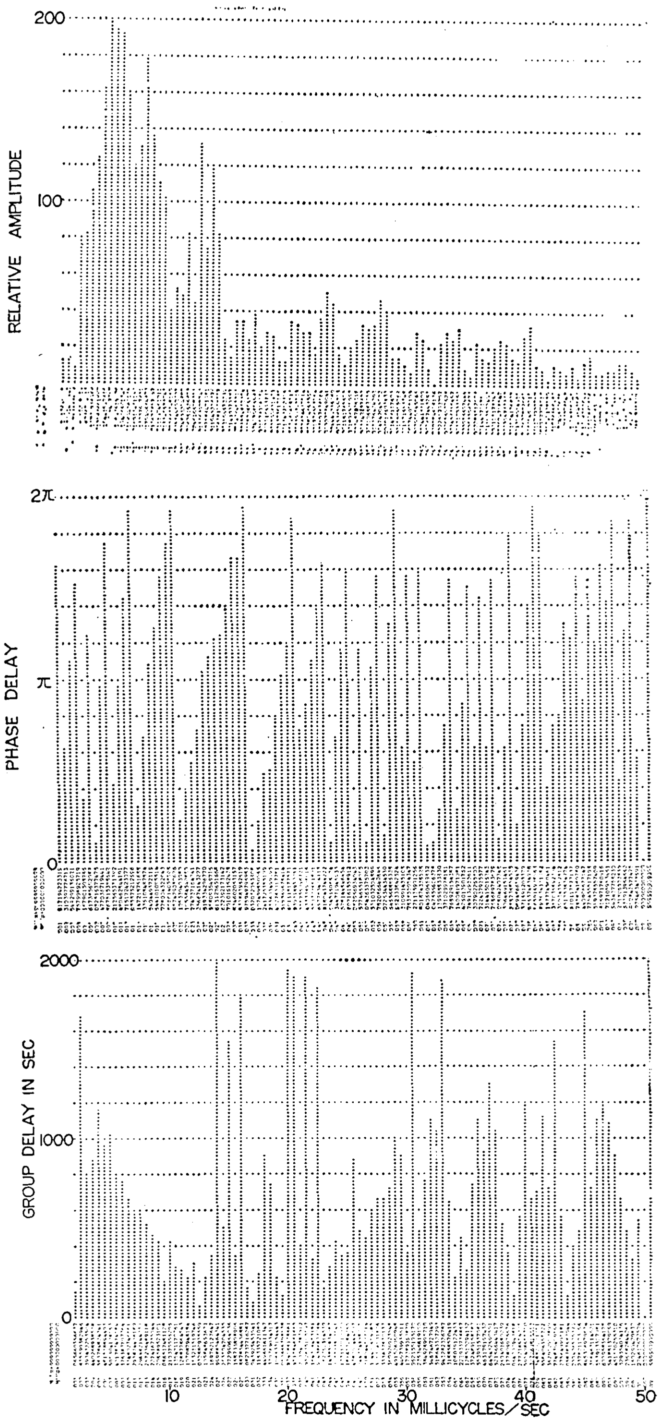


Fig. 11. Amplitude, phase delay and group delay spectra
the Ceram Sea Earthquake of Jan. 24, 1965. We notice a
(the same feature was observed also in the corresponding
verse dispersion character of mantle Rayleigh waves (fre-
in the group delay spectra.



of Rayleigh waves (R2 on the left, R3 on the right) from sinusoidal variation in the amplitude Spectrum for R2 spectrum obtained by a horizontal seismograph). The in-quencies lower than 15 millicycles per sec) is clearly shown out, (5) amplitude, phase delay and group delay spectra for each event. The purpose of this library is to facilitate the study of earthquake source mechanism as well as of the propagation media from the spectra of surface waves. For example, Fig. 11 shows the sinusoidal variation in amplitude spectrum which may or may not indicate the multiple events[16] or the moving source.[17] A problem of this sort may be solved, if we examine these spectra for many earthquakes in relation to the source and media factors which affect the spectra. The phase delay spectra may be used for the phase velocity measurement and the group delay spectra for the group velocity measurement.

Analyses of digital data in time domain, that is, various digital filterings are also made on a semi-routine basis. A low-pass filter with a cut-off period at 20 sec is being applied to most of the events recorded. This is to suppress the short-period waves and make it easier to study the behavior of long waves.

Separate papers will be written on the details of the analysis method as well as on the result obtained from our digital data.

Acknowledgement

The writers express their thanks to Prof. Setumi Miyamura for his kind help and constant encouragement given in the course of the present study. The writers' thanks are also due to Prof. Takahiro Hagiwara for giving them kind help and valuable advice in the construction of seismograph station. Messrs. Masao Watanabe and Tadao Watanabe at the Tsukuba branch station gave the writers kind help for building the vault and operating the seismograph.

The construction of the sampling and digitizing equipment was done by the Oki Electric Industry Co.. We would like to thank Mr. Kiichiro Akimoto and the staff of the Development Division of the Research Institute of the company for their valuable suggestions.

This work was supported by Grant NSF-G-23003 of the National Science Foundation, the United States.

---

16) W. L. PILANT and L. KNOPOFF, *Bull. Seism. Soc. Amer.*, **54** (1964), 19-39.
17) A. BEN-MENAHEM and M. N. TOKSÖZ, *J. Geophys. Res.*, **68** (1963), 5207-5222.

24. ディジタル長周期無線地震計システム

地震研究所 安芸敬一・松本英照・辻浦賢・丸山卓男

筑波山麓の地震研究所支所に長周期地震計用の観測点を新設した. 地震計は直結式で振子周期 15 秒, 検流計周期は 90 秒である. 検流計のふれは, 特殊な光学変換器を用いて, パルス位置変調の電気的信号となり, 東京本郷の地震研究所新館まで無線によつて送られる. 受信点で, 信号は 10 進 3 桁の数値に変換され紙テープ上に記録される. 同時に上 2 桁はアナログ変換されて常時自動平衡型記録器によつて記録される. サムプル間隔は 2 秒, ダイナミックレンヂは 59 db である.

地震計は, 表面波の振幅位相スペクトラムの研究を目的としてつくられたもので, 単能化しているため, 万能型のものより, 編集処理が著しく簡単化されている.

ルーテインとして行つている編集, 訂正, スペクトル分析についてのべてある.