

$$\begin{aligned} \bar{\phi}_r(r, \omega_0) &= \frac{1}{2} P(\omega_0) \left\{ J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) + J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \right\}, \\ \bar{\phi}_\phi(r, \omega_0) &= \frac{1}{2} P(\omega_0) \left\{ J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) - J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \right\}. \end{aligned} \quad (50)$$

(6) The velocity distribution function for a two dimensional wave is written in the form,

$$\frac{p(\omega_0, c)}{P(\omega_0)} = \frac{\omega_0}{c^3} \int_0^\infty \bar{\rho}(r, \omega_0) J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) r dr. \quad (62)$$

## Chapter 2. Apparatus

Theoretical considerations in Chapter 1 have shown that the spatial autocorrelation coefficient of the filtered waves plays an important role in the spectral study of stationary stochastic waves. In order to obtain the value of the coefficients with respect to a given wave, it is necessary first to filter the vibration of every seismometer by a resonator

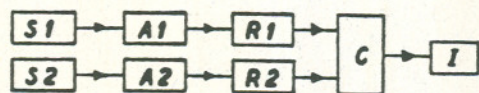


Fig. 1. Block diagram of apparatus.

S; seismometer  
A; amplifier  
R; resonator  
C; correlation computer  
I; indicator

having a certain assigned frequency, and secondly to compute the correlation coefficient for every pair of the filtered vibrations. Fig. 1 is the block diagram of an assembly of apparatus corresponding to one pair of seismometers. In the study of waves from the viewpoint of "phases", the recording of vibration is essential for identifying the phases and for reading travel times. In our method, on the other hand, what we need is not the original record, but the result of the above described operations applied to them. Those operations may be carried out manually, but it should be emphasized that the troublesome labours involved in the manual operations make the application of our method practically impossible. The present study has been made possible by the automation of the operations. In fact, the theoretical studies given in Chapter 1 were initiated after the completion of a correlation computer in our laboratory, though the use of filters in our method was based on the theoretical results.

Of the elements constituting our apparatus shown in Fig. 1, seismo-

meters are detailed elsewhere.

### 1. Filter

This type of fundamental filter is equal to the input voltage of the frequency phase angle on the frequency follows; the zero frequency is  $f_0 = 1/2\pi RC$  is circuits are constant phase angle for the whole for the neighborhood the corresponding  $\pi$ . Putting the phase inverter grid of the first feedback for the for the else. frequency  $f_0$ .

For the pur- tors having the frequency should of waves to be first object of our frequency range cov of resonance frequency resistances in

A filter of the ing inductances, to stable operation for



$$\left. \begin{aligned} & c(\omega_0) r \} , \\ & c(\omega_0) r \} . \end{aligned} \right\} \quad (50)$$

r a two dimensional wave

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meters and amplifiers are the ordinary ones, and we need not give any detailed explanation about them. We shall describe in this chapter the details of our filter and correlation computer.

### 1. Filter of phase shift type

This type of resonator is rather well known in Electronics. The fundamental part of this circuit is shown in Fig. 2. If the resistance  $r$  is equal to  $r_2$ , the ratio of the amplitude of output voltage to that of input voltage becomes 1.2 independent of the frequency of the input, while the phase angle shifted by the circuit depends on the frequency. This dependence is as follows; the phase angle shifted for the zero frequency is  $\pi$ , that for the infinite frequency is 0, while that for the frequency  $f_0 = 1/2\pi RC$  is  $\pi/2$ . Therefore, if two such circuits are connected in series, the resultant phase angle shift will be nearly zero for the whole range of frequency except for the neighbourhood of  $f_0 = 1/2\pi RC$ , where the corresponding angle is nearly equal to  $\pi$ . Putting the resultant output into a phase inverter and putting the output of the inverter to the control grid of the first valve of the phase shift circuit result in a positive feedback for the neighbourhood of the frequency  $f_0$  and a negative one for the else. Thus the circuit as a whole works as a resonator of frequency  $f_0$ .

For the purpose of the present study we need at least two resonators having the same characteristics, and moreover their resonance frequency should cover a considerable range which depends on the nature of waves to be studied. Since microtremors due to traffic will be the first object of our study, the resonators were designed to have a frequency range covering continuously from 5 c/s to 30 c/s. The variation of resonance frequency in the resonator was made by the use of variable resistances in the phase shift circuit.

A filter of this type is much easier to construct than a filter having inductances, but the  $Q$  value attainable is rather low. In our case, stable operation for a long time was not possible at a value of  $Q$  higher

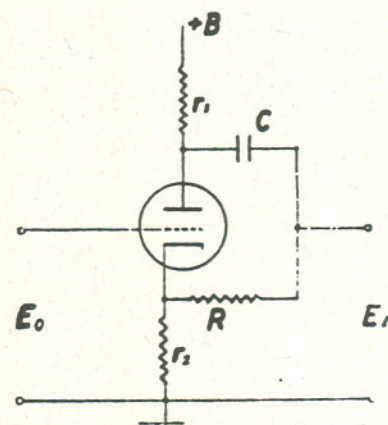


Fig. 2. Circuit for phase shift.



than 30.

At the time of observation, we must adjust the characteristics of the two filters in order that the resonance frequencies and  $Q$  values of both will be equal. For this purpose we are using a standard oscillator and an oscilloscope as shown in Fig. 3. At first the frequency of one of the filters is adjusted to be equal to an assigned frequency of the standard oscillator by the aid of the Lissajous' figure on the oscilloscope, and then the frequency of the other filter is adjusted to be equal to the assigned frequency in the same way. The  $Q$  value of our filter depends on the feedback constant which is controlled by a variable resistance. In order to equalize the  $Q$  values of the two filters, we connect the output of one of the filters to the horizontal input of the oscilloscope and that of the other to the vertical one, and observe the response figure caused by the simultaneous application of an impulse to both filters. If the response figure on the oscilloscope diminishes in size keeping a similar shape, we regard that the adjustment is finished.

## 2. Automatic computer of the correlation coefficient

A computer for calculating the correlation coefficient according to the ordinary way needs the following parts; an input device such as tape or card system, arithmetic elements to make additions and multiplications, and an output device such as a printing machine or some other indicators. So far as we stick to this customary method of computation, the computing machine will become a large one, which cannot be very inexpensive. But if we use the simplified method proposed by Tomoda<sup>3)</sup> (1956), the computer will become a very simple one.

In the method due to Tomoda, the original stochastic variable is replaced by +1 when it is above the mean value, and by -1 when it is below the mean value. Then the computation of the correlation coefficient in the ordinary way is applied to the resultant series of +1 and -1. If this value obtained is  $r$ , the true correlation coefficient  $\rho$  is deduced by the following formula,

$$\rho = \sin \frac{\pi}{2} r.$$

Since the mean value of the deflection of a seismometer pendulum can

be assumed :

where  $n_+$  is the number of the seismic pulses which is the number

This simplified analysis by Aki compared the method with the agreement given time series simplified method is actually almost sinusoidal

The parts of circuits to compare seismometers with a counting tube as

At first we consider for which the signal have the positive multivibrator triggering in the following 6SA7, having two pulses coming from the seismometer pulses as shown proportional to the positive sign. Therefore putting a vibrator, we obtain signal from  $S_1$  has same height as signal applied to the above from the generator

3) Y. TOMODA, *Jour. Phys. Earth*, 4 (1956), 67.

4) K. AKI, *Jour. I.*

5) K. AKAMATU, *il.*



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be assumed as zero, we can write the above  $r$  in the form,

$$r = \frac{n_+ - n_-}{n_+ + n_-}$$

where  $n_+$  is the number of sample pairs for which the deflection of one of the seismometers has the same sign as that of the other, while  $n_-$  is the number of sample pairs for which their signs are opposite.

This simplified method was applied to seismograms in a correlogram analysis by Aki<sup>4</sup> (1956) which proved its effectiveness. Akamatu<sup>5</sup> (1956) compared the correlogram of a given time series obtained by this method with that obtained by the customary method, and showed that the agreement between them is satisfactory, as the wave form of the given time series is not very complicated. The application of this simplified method in the present case is justified because the computation is actually made with regard to the filtered vibration having an almost sinusoidal wave form.

The parts of our computer are as follows; a generator of pulses, circuits to compare the sign of the signal coming from one of the seismometers with that from the other, and decatron which works as a counting tube as well as an indicator.

At first we shall describe how to count the number of sample pairs for which the signal from the seismometer  $S_1$  and that from  $S_2$  both have the positive sign. Pulses from a generator, which is a one shot multivibrator triggered by a thyratron oscillator, play the part of sampling in the following way. If we use a frequency converting valve, e.g. 6SA7, having two control grids, of which one is fed by the series of pulses coming from the generator and the other by the signal coming from the seismometer  $S_1$  as shown in Fig. 5, the output is a series of pulses as shown in Fig. 4-c. The height of each pulse is now proportional to the height of the signal from  $S_1$ , when the latter has the positive sign. When it is negative, no output pulses will appear. Therefore putting this series of output pulses into another one shot multivibrator, we obtain the series of pulses which appear only when the signal from  $S_1$  has the positive sign. These pulses are now of the same height as shown in Fig. 4-d. Finally, if the same operation is applied to the above pulses and the signal  $S_2$  as is done to the pulses from the generator and the signal from  $S_1$ , we have the series of pulses

4. K. AKI, *Jour. Phys. Earth*, 4 (1956), 71.

5. K. AKAMATU, *ibid.*, 81.



which appear only when both the signals from  $S_1$  and from  $S_2$  have the positive sign as shown in Figs. 4-e, 4-f and 4-g.

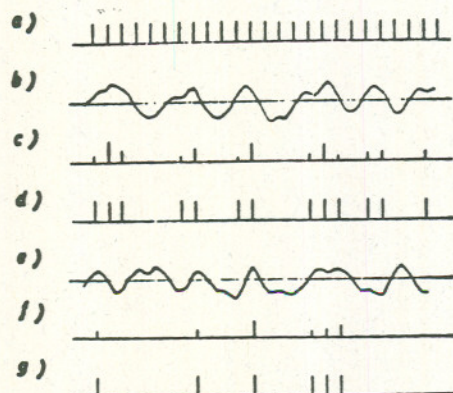


Fig. 4. Process of computation shown schematically.

- a) pulses from a pulse generator,
- b) signal from the seismometer 1,
- c) and d) pulses which exist when the signal from  $S_1$  is positive,
- e) signal from the seismometer 2,
- f) and g) pulses which exist when the signals from both seismometers are both positive.

The series of pulses which appear when both of them have the negative sign will be generated in the same way as above except for the use of phase inverters applied beforehand to the signals from both seismometers. The two series of pulses thus obtained are counted in a decatron circuit, and the number  $n_+$  of the sample pairs for which the signs of the signals from both seismometers are the same is obtained. Since we are using three decatrons in series, we can count up to one thousand. The processes above described may be understood by the block diagram in Fig. 6.

The counting of  $n_-$  is carried out in the same way as that of  $n_+$  but with the reverse connection of the outputs of one of the inverters.

The result of counting is indicated on the decatrons. Photographs

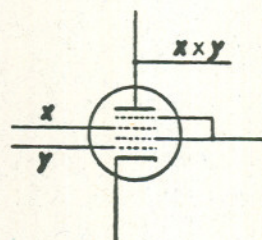


Fig. 5. 6SA17 as a multiplier.

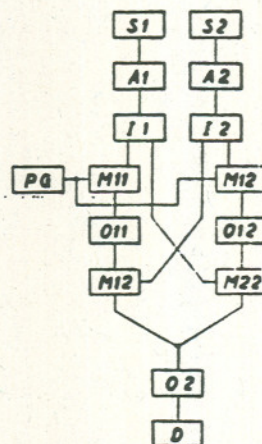


Fig. 6. Block diagram of computer.

- $S$ ; seismometer
- $A$ ; amplifier
- $I$ ; phase inverter
- $M$ ; multiplier
- $PG$ ; pulse generator
- $O$ ; one-shot multi-vibrator
- $D$ ; decatrons

of our comp  
Fig. 8.

### 3. Remarks

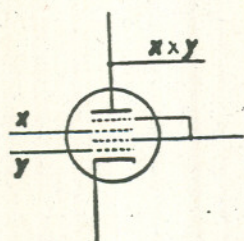
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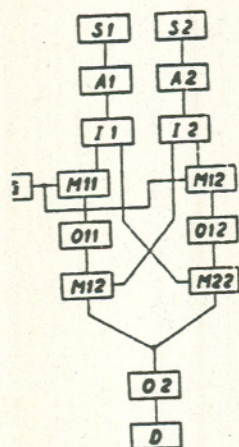
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5. 6S.17 as a multiplier.



Block diagram of computer.

ismometer  
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catrons

multiple pairs for which the correlation coefficient is the same is obtained. We can count up to one hundred pairs to be understood by the

same way as that of  $n$ , of one of the inverters. decatrons. Photographs

of our computer and the decatron indicator are shown in Fig. 7 and Fig. 8.

### 3. Remarks

The choice of the time interval of successive pulses from the generator depends on the nature of waves to be studied. Since our primary object was microtremors of traffic origin, the time interval was taken as 1/50 second considering that the predominant period of the tremors is 1/10 second. Of course, not only the pulse interval but also the frequency range of the resonator and the characteristics of the seismometers should be appropriate to the spectral nature of the waves concerned. The whole apparatus designed for microtremors will be applied without modifications to volcanic tremors or to ground motions having rather high frequencies caused by some meteorological disturbances. On the other hand, in order to investigate waves having lower frequencies, we need some modifications of the apparatus.

As far as we are concerned with almost perfectly stationary waves, that is waves having sufficiently long durations that we can, not only obtain the correlation coefficients from large samples, but also repeat the measurement several times under the same circumstances, we need only one set of apparatus, i.e. a pair of seismometers, a pair of filters, and one correlation computer. There is, however, another important class of waves having intermediate durations, which are long enough for the computation of correlation coefficient, but nevertheless are too short for repeated measurements. To this class of waves belong some parts of the seismic waves of earthquake origin. The measurement of this latter kind of waves will be very difficult without the use of storage units such as magnetic tapes or magnetic discs.

We shall note some features of the apparatus which seem peculiar to the present method. Since a very sharp filtration is applied to the vibration, troubles with the noises in the amplifier such as caused by the hum in the power source are considerably diminished. In addition, since the correlation between the simultaneous vibrations at two points is under question, the uneven phase lag and amplification as to the frequency on the part of the seismometer and the amplifier cannot be serious matters, for the pair of seismometers and also of amplifiers are made to have identical characteristics.



### Chapter 3. Microtremors

In this chapter, our method described in the preceding chapters will be applied to microtremor analyses. The microtremor studied for this purpose is believed to be caused by traffic and appears as an undesirable background noise in many precise geophysical measurements. The choice of this as our object is partly due to the handiness of its measurement as a trial application of our method but also due to the fact that the microtremor itself has formed one of the important problems in Seismology, especially in Japan.

It is well known that the characteristics of the ground are reflected more or less in its vibration whatever the origin of the vibration may be. This fact was noticed early in the beginning of this century by K. Sekiya and F. Omori who made a comparative study of seismograms recorded at Hongo and Hitotsubashi, both in Tokyo. Later, many Japanese seismologists studied ground vibrations from the view point of frequency spectrum. Among them, M. Ishimoto<sup>6)</sup> (1937) made a systematic study both of vibrations due to earthquakes and of the background tremors, and proposed a hypothesis that the predominant period of vibration due to earthquakes coincides with that of the background tremors.

Though some negative results against the above hypothesis have been obtained by P. Byerly<sup>7)</sup> (1947) and by K. Aki<sup>8)</sup> (1955), the spectral study of the background tremors was succeeded in by various authors.

Y. Tomoda and K. Aki<sup>9)</sup> (1952) made a frequency analysis by the use of a spectrometer, and confirmed the fact that vibrations having frequencies higher than 1 c/s are due to traffic. K. Kanai, T. Tanaka and K. Osada<sup>10)</sup> (1954) made an extensive study and showed that the form of the spectral distribution of microtremors coincides with that of earthquake motions, and that it depends on the geology of the place. K. Akamatsu<sup>11)</sup> (1956) investigated the tremors observed at Hongo in more detail from the view point of correlograms in space and time.

6) M. ISHIMOTO, *Bull. Earthq. Res. Inst.*, **15** (1937), 697.

7) P. BYERLY, *Bull. Seis. Soc. Amer.*, **37** (1947), 291.

8) K. AKI, *Zisin*, [ii], **8** (1955), 99.

9) Y. TOMODA and K. AKI, *Zisin*, [ii], **5** (1952).

10) K. KANAI, T. TANAKA and K. OSADA, *Bull. Earthq. Res. Inst.*, **32** (1954), 199.

11) K. AKAMATSU, *Zisin*, [ii], **9** (1956), 21.

Ishimoto layer, and authors. In summing the

#### 1. Preliminary

It will be of the type of the following

A. A surface wave. Y. Sato<sup>12)</sup> (1941) along the horizontal given. If we a definite velocity by which the will take the

B. The vertically propagating body wave surface wave (1941); it was shows predominance  $5V/4H$ , etc., where  $H$  is the thickness of the spatial auto ed by a resonant dent of the distance

C. The vertically propagating body wave surface wave (Takayama<sup>13)</sup> (1956) case. We assume consists of various angles. The vibration in the narrow sense this wave along given. If our model distribution of velocity

12) Y. SATO, *Bull.*

13) R. TAKAHASHI

14) G. NISHIMURA



the preceding chapters microtremor studied for and appears as an un-physical measurements. to the handiness of its method but also due to the fact that one of the important

of the ground are reflected in of the vibration may bring of this century by intensive study of seismograms in Tokyo. Later, many are from the view point of Aki (1937) made a systematic study of the background and of the predominant period of that of the background

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frequency analysis by the fact that vibrations having been studied by K. Kanai, T. Tanaka and showed that the period coincides with that of the geology of the place. as observed at Hongo in measurements in space and time.

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*Bull. Earthq. Res. Inst.*, **32** (1954), 199.

Ishimoto's hypothesis implies a resonance phenomenon in the surface layer, and this problem has been attacked theoretically by various authors. In the following section, we shall refer to some of them assuming the hypothetical wave type of the microtremors.

### 1. Preliminary discussions

It will be useful to make a preliminary consideration about the wave type of the microtremors. It may be assumed that the type is one of the following four.

A. A surface wave in a narrow sense; this terminology is due to Y. Sato (1954), and represents the wave having an apparent velocity along the horizontal surface which is determined if the frequency is given. If we apply our method to the wave of this type, we can obtain a definite velocity corresponding to a given frequency of the resonator by which the vibrations are filtered. And the autocorrelation function will take the form of Eq. (41), Eq. (49), or Eq. (50).

B. The vibration of a soft surface layer due to a vertically incident bodily wave such as that dealt with by R. Takahasi and K. Hirano (1941); it was shown in their paper that the vibration of this type shows predominant amplitudes at the frequencies,  $f = V/4H$ ,  $3V/4H$ ,  $5V/4H$ , etc., where  $V$  is the velocity of bodily wave in the layer and  $H$  is the thickness of the layer. It will be expected in this case that the spatial autocorrelation coefficient with respect to the vibration filtered by a resonator having the predominant frequency, becomes independent of the distance  $r$  and is equal to unity.

C. The vibration of a surface layer due to an obliquely incident bodily wave which was studied for instance by G. Nishimura and T. Takayama (1939); a kind of resonance phenomena is observed in this case. We assume that the microtremor belongs to this type, and consists of various vibrations resulting from waves of different incident angles. The vibration of this type is evidently not the surface wave in the narrow sense defined by Y. Sato, because the apparent velocity of this wave along the surface cannot be definite even if the frequency is given. If our method is applied to the wave of this type, a continuous distribution of velocity, that is described in Sections 3 and 9 of Chapter

12. Y. SATO, *Bull. Earthq. Res. Inst.*, **32** (1954), 161.

13. R. TAKAHASI and K. HIRANO, *Bull. Earthq. Res. Inst.*, **19** (1941), 534.

14. G. NISHIMURA and T. TAKAYAMA, *Bull. Earthq. Res. Inst.*, **17** (1939), 253-268.



$$e^{-\alpha f d} \quad \alpha = 0.1^{-1/5}$$

1, will be observed instead of definite velocities.

D. The vibration due to a periodically distributed surface disturbance such as that illustrated in the paper of K. Sezawa and K. Kanai<sup>15)</sup> (1937); it was shown that a resonance phenomenon occurs when the frequency of vibration is equal to the solution of the characteristic equation of a surface wave for the wave length which is equal to that of the distribution of given disturbance. In this case, the form of spatial autocorrelation coefficients with respect to the vibrations filtered by resonators of various frequencies will be independent of the frequency, and will be determined by the spatial pattern of the given disturbance.

Bearing the above four types in mind and applying our correlational analyses to the microtremor at Hongo, in Tokyo, we shall be able to determine its wave type together with its several important characteristics.

## 2. Microtremors at Hongo

The measurement was made in the yard of the Geophysical Institute of Tokyo University, of which a map is shown in Fig. 9. In this map are shown the lines along which the spatial autocorrelation is obtained, three wooden buildings by thin line rectangles and an abandoned tennis court by a dotted line rectangle. This is the same place where K. Akamatsu (1956) studied the spectrum of prevailing microtremors. The predominant frequencies of the tremors were found by her to lie at 3~4 c/s and at 7~10 c/s. In the present study, we shall deal with the vibrations having frequencies higher than 5 c/s, leaving the vibrations having lower frequencies including 3~4 c/s to a later study.

Seismometers used in the present investigation are all of the moving coil type; a pair of horizontal ones having the free frequency of 10 c/s, a pair of horizontal ones of the frequency of 4.5 c/s, and a pair of vertical ones of the frequency of 4.5 c/s.

15) K. SEZAWA and K. KANAI, *Bull. Earthq. Res. Inst.*, 14 (1938), 1.

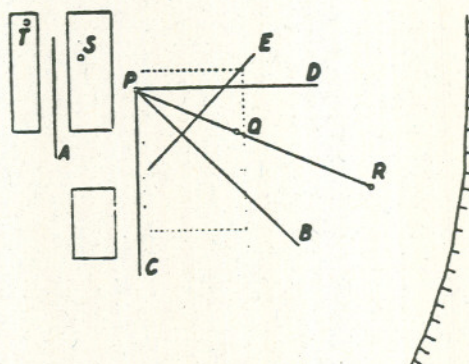


Fig. 9. Map showing lines of measurement.

The observation time from 11 to 12 is severely by the weather.

At the time the set up along the lines are sent through the autocorrelation analysed by the autocorrelation coefficient. The autocorrelation coefficient is notably with the autocorrelation coefficient, for varying from 0 to 10 minutes or ten minutes than five thousand.

## 3. Direction of measurement

Fig. 10 shows the autocorrelation lines B, C, D, E, and R, which are meters having a length of 10 meters.

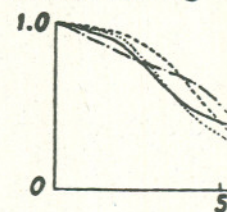


Fig. 10. Autocorrelation curves for various directions.

autocorrelation function for various spatial angles. (See Fig. 11.)

## 4. Horizontal bearing

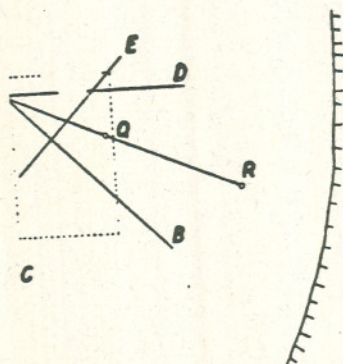
It was found that the autocorrelation is high along a segment of the line along another segment of the line, where the dotted line is taken along the line along QR. In both cases, such a direction as



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K. Sezawa and K. Kanai<sup>(15)</sup>  
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st., 14 (1938). 1.

The observation of the tremors was usually made during the night time from 18h to 22h, because the daytime observation is disturbed severely by the noise due to persons walking in and around the place.

At the time of measurement, one of the pairs of seismometers is set up along the line of measurement, and the signals coming from them are sent through wires to the amplifiers placed in the laboratory to be analysed by the resonators and the correlation computer. The correlation coefficient obtained from the sampling during a short period varies notably with time, for instance, 50 second sampling yields the correlation coefficient, for a seismometer pair 20 meters apart from each other, varying from 0.5 to -0.9. Therefore a sampling time of at least five or ten minutes is needed, this corresponding to the sample size of more than five thousands.

### 3. Direction of propagation

Fig. 10 shows the autocorrelation coefficients measured along the lines B, C, D, and E in Fig. 9. In this measurement, horizontal seismometers having the frequency of 10 c/s are used and filtration is not applied. Since the curves in the figure differ only slightly from one another, we may regard the micro-tremor as being propagated in every direction, each with almost uniform power. Thus it may be allowed to replace the azimuthally averaged autocorrelation function by the autocorrelation function taken along any line having an arbitrary azimuthal angle. (See Section 8, Chapter 1.)

Fig. 10. Autocorrelation coefficients for various directions.

### 4. Horizontal heterogeneity

It was found, however, that the autocorrelation coefficient taken along a segment of a line sometimes differs significantly from that taken along another segment of the same line. An example is shown in Fig. 11, where the dotted curve represents the autocorrelation coefficient taken along the line segment PQ, and the other curve shows that taken along QR. In both cases, the horizontal seismometers are set up in such a direction as to be sensitive to the vibration which is perpendi-



cular to the line, and the signals from them are filtered by resonators of frequency 9.0 c.s. This fact evidently shows that the wave in question is not stationary in space and can not be adequately dealt with by the present method. We can, however, partly get rid of this difficulty by dealing with the wave within smaller confined areas individually. This may be justified by the fact that the above heterogeneity is due to the existence of the abandoned tennis court covered by a hard surface soil. The fatal difficulty was caused by this heterogeneity in the reduction of the velocity distribution function which was introduced in Sections 3 and 9, Chapter 1, because for its reduction the values of correlation coefficient between two seismometers reasonably apart from each other is needed.

Under this circumstance the distinction between the type A and C mentioned in Section 1 may fail to be drawn clearly. We may, however, identify the type of our wave as A, if a wave having a single and definite velocity is predominant in the wave and the obtained correlogram has a simple form.

### 5. Horizontal motions

Before presenting the result of measurements, we shall look back at the theoretical considerations given in Chapter 1. If a certain type of polarized wave is predominant in microtremors, the autocorrelation function with respect to the wave filtered by a resonator of frequency  $\omega_0$  will be given either in the form (49) or in the form (50), depending on the mode of polarization. Since we can assume that both  $\phi_r(0, \psi)$  and  $\phi_s(0, \psi)$  are independent of the azimuthal angle  $\psi$  in this case, we have the following autocorrelation coefficients for the parallel polarization,

$$\left. \begin{aligned} \rho_r(r, \omega_0) &= J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) - J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \\ \rho_s(r, \omega_0) &= J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) + J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \end{aligned} \right\} \quad (63)$$

while for the perpendicular polarization,

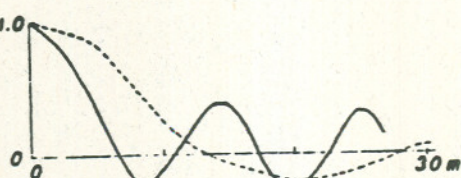


Fig. 11. Comparison of autocorrelation coefficients measured along the lines PQ and QL.

where  $\rho_r(r, \omega_0)$  is the autocorrelation coefficient measured along the line PQ and the curves  $J_0(x)$ .

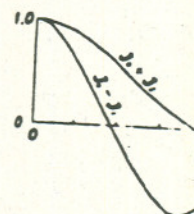


Fig. 12. Curves  $J_0(x)$  and  $-J_2(x)$ .

Table I.

1st zero
1st min.
2nd zero
1st max.
3rd zero
2nd min.
4th zero

The azimuthal motion of frequency  $\omega_0$  is shown as a whole  $J_0(x)$  and minima for the first time in the 1st zero obtained in such a point Q, while the point Q is attributed to the shown in Fig. 9. If we measure



e filtered by resonators  
that the wave in ques-  
adequately dealt with by  
get rid of this difficulty



Comparison of autocorrelation  
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l angle  $\psi$  in this case, we  
for the parallel polarization,

$$\left. \begin{aligned} & \rho_r(r, \omega_0) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) + J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \\ & \rho_\psi(r, \omega_0) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) - J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \end{aligned} \right\} \quad (63)$$

$$\left. \begin{aligned} \rho_r(r, \omega_0) &= J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) + J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \\ \rho_\psi(r, \omega_0) &= J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) - J_2\left(\frac{\omega_0}{c(\omega_0)} r\right) \end{aligned} \right\} \quad (64)$$

where  $\rho_r(r, \omega_0)$  and  $\rho_\psi(r, \omega_0)$  are the autocorrelation coefficients for the azimuthal and radial components of vibrations respectively. In Fig. 12



Fig. 12. Curves of  $J_0(x) + J_2(x)$  and  $J_0(x) - J_2(x)$ .

the curves  $J_0(x) - J_2(x)$  and  $J_0(x) + J_2(x)$  are plotted. With the aid of a table of Bessel functions, the arguments giving the zero, maximum and minimum values of the above curves together with the values of the maxima and minima can be obtained as given in Table I.

First will be given the result of measurements along the line segment QR in the map in Fig. 9.

Table I. Arguments giving the zeros, maxima and minima.

	$x$	$J_0(x) - J_2(x)$	$x$	$J_0(x) + J_2(x)$
1st zero	1.85	0	3.9	0
1st min.	3.50	-0.85	5.1	-0.14
2nd zero	5.35	0	7.0	0
1st max.	6.75	0.62	8.5	0.07
3rd zero	8.55	0	10.0	0
2nd min.	10.1	-0.5		
4th zero	11.7	0		

The azimuthal component of autocorrelation coefficient of the horizontal motion of frequency 9 c/s along this line segment is already given by a full line curve in Fig. 11 in the preceding section. This curve resembles as a whole  $J_0(x) - J_2(x)$  in Fig. 12 in form, and the values of the maxima and minima for these two are almost equal except for a notable difference in the 1st minimum value. Since the correlation coefficient is obtained in such a way that one of the pair of seismometers is fixed at the point Q, while the other is moved along QR, this difference may be attributed to the effect of the hard surface soil of the tennis court shown in Fig. 9.

If we measure the correlation coefficient for various frequencies  $\omega_0$



and for a fixed distance  $r$ , we have the result as shown in Fig. 13, where the distance is 25 meters, and the direction of vibration is perpendicular to  $QR$ . This measurement was repeated three times, each on different days but at almost the same hour. Fig. 13 shows that the autocorrelation curve is well reproducible. Also it can be seen that the first maximum of the curve appears at the frequency of 6.4 c/s, and the maximum value amounts to 0.66 which is almost equal to the corresponding value of  $J_0(x) - J_2(x)$ .

These facts suggest that we may assume that the predominant wave in the horizontal motion of microtremor is the one having a single definite velocity and being polarized in the direction perpendicular to that of propagation. Then we can obtain the velocities for various frequencies by identifying the zeros, maxima and minima of the curve in Fig. 13 with those given in Table I. For instance, we have the following equation corresponding to the first maximum,

$$2\pi \cdot 6.4(\text{c/s}) \cdot \frac{25(\text{m})}{C_{e,1}} = 6.75.$$

Thus the wave velocity for the frequency 6.4 c/s is obtained as 148 m/s. The velocities for various frequencies are plotted in Fig. 17 by the mark  $\circ$ .

A similar measurement is made for the seismometer pair 15 m apart from each other. The resultant autocorrelation coefficient is plotted against the frequency of resonators in Fig. 14. The wave velocities are

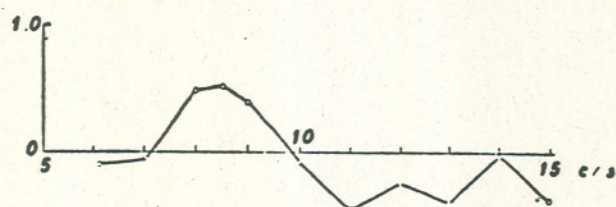


Fig. 14.  $\rho(\omega_0, r)$ , for  $r=15$  m, plotted against  $\omega_0$ .

velocity values obtained from two independent measurements as shown in Fig. 17.

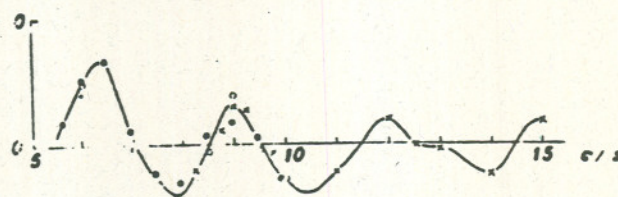


Fig. 13.  $\rho(\omega_0, r)$ , for  $r=25$  m, plotted against  $\omega_0$ .

Fig. distance seismome surface s cal one, deduced.

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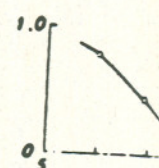


Fig. 15.  $\rho(\omega_0, r)$

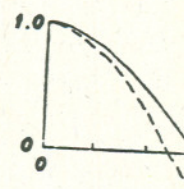


Fig. 16. Compari hal and radial

that the value for the azimuth slightly larger t Moreover, the a than that for th tion that the hor ing the zeros, m  $+J_2(x)$  given in 7 frequencies as show Fig. 17 clearl dependent measur smooth curve. Th predominant wave one having a single



ult as shown in Fig. 13, tion of vibration is per- ceated three times, each



$r=25$  m, plotted against  $\omega$ .

amounts to 0.66 which is  $J_0(x) - J_2(x)$ .

that the predominant wave is one having a single direction perpendicular to that of the velocities for various frequencies. The minima of the curve in Fig. 13, we have the following

1.

4 c/s is obtained as 148 m/s. plotted in Fig. 17 by the

a seismometer pair 15 m apart. The correlation coefficient is plotted in Fig. 14. The wave velocities are obtained from this curve in the same way as stated in the preceding paragraph, and are plotted also in Fig. 17 by the mark  $\bullet$ . A good coincidence is observed between the independent measurements as shown

Fig. 15 shows the result of a similar measurement in which the distance between the seismometers is 7.5 m. Since in this case the seismometers are placed too near the tennis court covered by hard surface soil, the departure of the autocorrelation curve from the theoretical one,  $J_0(x) - J_2(x)$ , is considerable, and the velocities cannot be deduced.

A similar measurement is also made about the radial component of the autocorrelation coefficient of the horizontal motion, and the result is shown in Fig. 16 by a full line, where the distance between two seismometers is 25 m.

It is confirmed, by observing correlations for a fixed frequency and various distances, that the maximum which appears in Fig. 16 at the frequency of about 7.3 c/s is the first maximum. Therefore the extrapolation of the curve toward lower frequencies as in Fig. 16 is justified at least as a general trend. It is clear from the figure

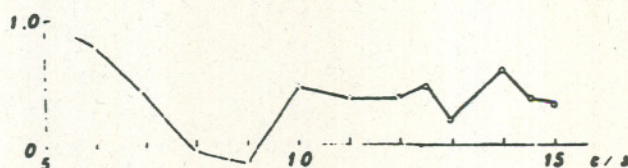


Fig. 15.  $\mu(\omega, r)$ , for  $r=7.5$  m, plotted against  $\omega$ .

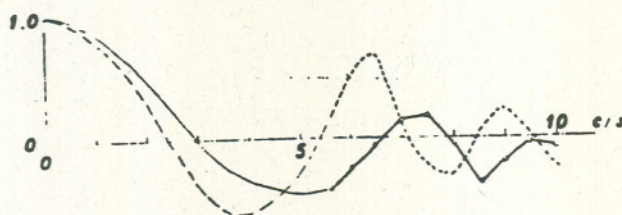


Fig. 16. Comparison of correlation curves for azimuthal and radial components.

that the value of the first maximum is very small compared with that for the azimuthal component which is shown by a dotted line, and slightly larger than that of  $J_0(x) + J_2(x)$  which is theoretically expected. Moreover, the argument giving the first maximum is evidently larger than that for the azimuthal component, strongly confirming the assumption that the horizontal motion is polarized perpendicularly. By identifying the zeros, maxima and minima of this curve with those of  $J_0(x) + J_2(x)$  given in Table I, we can obtain wave velocities for various frequencies as shown in Fig. 17 by the mark  $\times$ .

Fig. 17 clearly indicates that all the points obtained from three independent measurements are concentrated fairly well to form a single smooth curve. This fact shows the validity of our assumption that the predominant wave in the horizontal motion of the microtremors is the one having a single definite velocity for a given frequency and being



polarized in the direction perpendicular to that of propagation. In short, the predominant wave is of Love type and the curve in Fig. 17 is its dispersion curve.

### 6. Vertical motions

A similar measurement as applied to the horizontal motion is made about the vertical motion also along the line segment QR. It is evident that there is no polarization with respect to the vertical motion in the case of two dimensional waves. Therefore, if a wave having a definite velocity corresponding to a given frequency is predominant in the vertical motion, the autocorrelation coefficient will take the form,

$$\rho(r, \omega_0) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right),$$

which was derived in section 6, Chapter 1. The zeros, maxima, and minima of  $J_0(x)$  are given in Table II.

The result of measurement is shown in Fig. 18, where the correlation is taken between two vertical seismometers placed along QR and

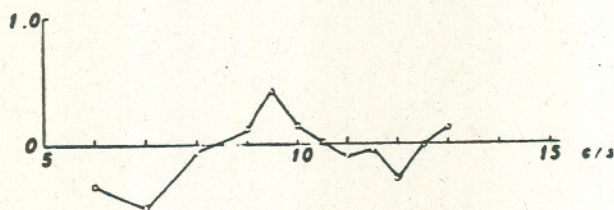


Fig. 18.  $\rho(\omega_0, r)$  of vertical motion, for  $r=25$ m, plotted against  $\omega_0$ .

25 m apart from each other. It is confirmed, by observing correlations for a fixed frequency and various distances, that the maximum of the correlation curve of the wave at the frequency 9.5 c/s is the first maximum, and the minimum at 7.0 c/s is the first minimum. From the

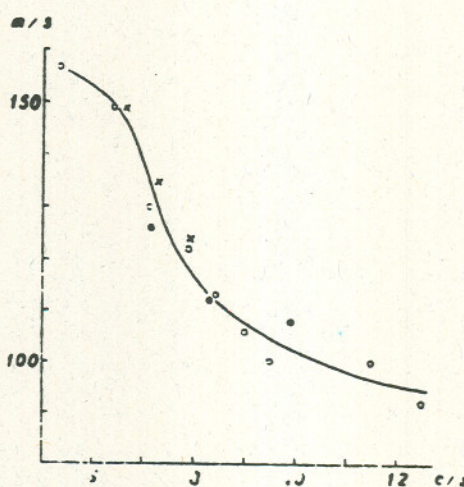


Fig. 17. Dispersion curve of horizontal motion.

Part 3.]

figure it can  
first minim  
assume that

1st zero  
1st min.  
2nd zero  
1st max.  
3rd zero

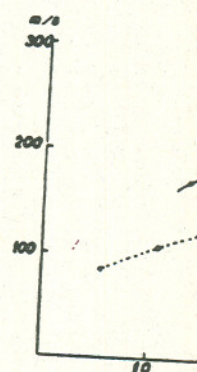


Fig. 19. Comparison of vertical motion (Abs) and theory. (Abs)

large as that fo  
indicated in Fig

### 7. The velocity

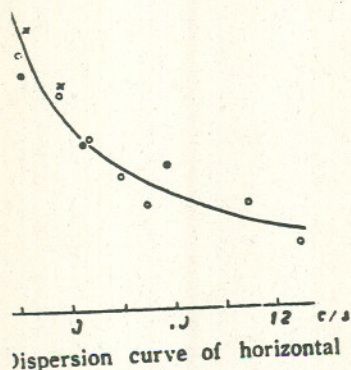
Recently T. waves propagating of determining the curve. According to zero at the surface equal to a given



figure it can be seen that the values of the first maximum and the first minimum are almost equal to those of  $J_0(x)$ . Thus we may assume that a surface wave in the narrow sense is predominant in the

Table II.  $J_0(x)$ .

	$x$	$J_0(x)$		$x$	$J_0(x)$
1st zero	2.40	0	2nd min	10.18	-0.250
1st min.	3.83	-0.403	4th zero	11.79	0
2nd zero	5.52	0	2nd max.	13.33	+0.218
1st max.	7.01	+0.300	5th zero	14.93	0
3rd zero	8.65	0			



ncy is predominant in the will take the form,

the zeros, maxima, and

Fig. 18, where the correla-  
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15 c/s

25m, plotted against  $\omega_0$ .

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that the maximum of the  
ncy 9.5 c/s is the first max-  
first minimum. From the

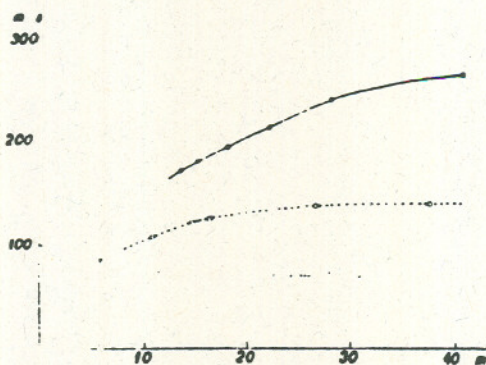


Fig. 19. Comparison of dispersion curves of  
vertical motion obtained from experiment  
and theory. (Abscissa is wave length.)

large as that for the horizontal motion identified as a Love wave, as indicated in Figs. 17 and 19.

## 7. The velocity of S wave at various depths

Recently T. Takahashi<sup>(6)</sup> (1955) studied the dispersion of Love type waves propagating over a heterogeneous medium, and gave a method of determining the structure of the medium from a given dispersion curve. According to him, if the derivatives of density and rigidity are zero at the surface, the depth  $z$  at which the velocity of S wave is equal to a given  $V_s$  can be found by the formula

$$Z(V_s) = \frac{1.11}{4\pi} V_s \int_0^{T_s} \left[ \left\{ \frac{V_s}{V_s(T)} \right\}^2 - 1 \right]^{-1/2} dT$$

16 T. TAKAHASHI, *Bull. Earthq. Res. Inst.*, **33** (1955), 287.



where  $T$  is the period of wave,  $V_Q(T)$  is the phase velocity of wave corresponding to a period  $T$ , and  $T_s$  is the period for which  $V_Q(T)$  is equal to  $V_s$ .

Introducing the phase velocity of the horizontal motion given in Fig. 17 into the above formula, we get the variation of  $S$  wave velocity with depth as shown in Fig. 20.

In this calculation, the surface values of the velocity and its derivative are assumed as 75 m/s and zero respectively. From Fig. 20 it can be seen that there is a rapid increase in velocity at depths from 2 m to 3.5 m, and above and below these depths the velocities are nearly constant respectively. This fact suggests a discontinuity of substance at the depth of about 2.7 m.

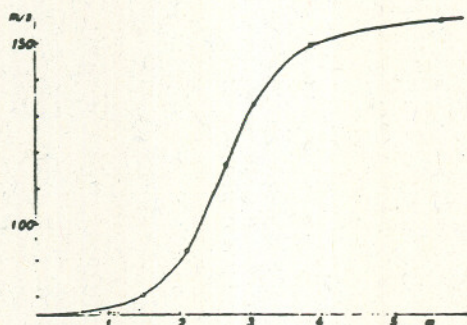


Fig. 20. Velocity of  $S$  wave at depths.

The dispersion curve of Rayleigh waves propagating over a layered surface was discussed by K. Sezawa<sup>17)</sup> (1927), and was shown graphically in the case of  $\lambda=\mu$ ,  $\lambda'=\mu'$ , and  $\rho=\rho'$ . If we assume a layer having thickness of 2.7 m with the velocity of  $S$  wave of 75 m/s, and a substratum with 160 m/s as suggested from the curve in Fig. 20, an application of Sezawa's result to such a structure yields a dispersion curve for Rayleigh wave as shown by a dotted line in Fig. 19. The figure shows a considerable discrepancy between the curve obtained by the measurement and that expected theoretically from the structure which is determined by the use of the dispersion curve of the Love wave.

This discrepancy may be attributed either to the difference between the velocity of the  $SV$  wave and that of the  $SH$  wave, or to a misidentification of the type of wave.

A similar phenomenon is reported in a paper by J. E. White, S. N. Heaps, and P. L. Lawrence<sup>18)</sup> (1956) in which a surface wave identified as Rayleigh wave is shown to have group and phase velocities about twice as large as those for Love wave:

17. K. SEZAWA, *Bull. Earthq. Res. Inst.*, **3** (1927), 1-18.

18. J. E. WHITE, S. N. HEAPS, and P. L. LAWRENCE, *Geophysics*, **21** (1956), 715.

## 8. An example

In this line segment been mentioned

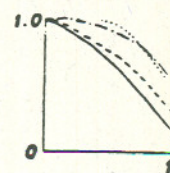


Fig. 21. Autocorrelation motion  
 $\omega_0=7.5$   
 $\omega_0=13.6$   
 $\omega_0=14.6$   
and  $\omega_0=21.2$

perpendicular shown in Fig. 21 must however, is a generality of the

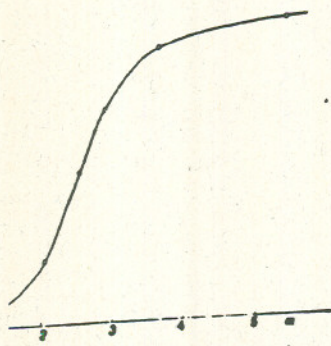
The most general trend almost independent of the existence of the structural attributes assume an almost proportional

The autocorrelation of vertical frequencies of 7 plotted against Fig. 22. Although the frequency of existence of wave lengths, coincides with



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velocity of  $S$  wave at depths.

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aper by J. E. White, S. N.  
a surface wave identified  
nd phase velocities about

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E, *Geophysics*, 21 (1956), 715.

### 8. An example of anomalous dispersion

In this section will be given the result of measurement along the line segment  $PQ$  in the tennis court as shown in Fig. 9. As has often been mentioned previously, this place is covered by hard surface soil.

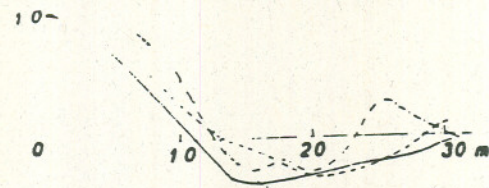


Fig. 21. Autocorrelation coefficients of horizontal motion along the line  $PQ$  for

$\omega_0 = 7.5$  ————,  
 $\omega_0 = 13.6$  ————,  
 $\omega_0 = 14.6$  ————,  
and  $\omega_0 = 21.2$  ————.

Fig. 21 indicates the autocorrelation coefficients with respect to waves filtered by resonators having frequencies 7.5, 13.6, 14.6 and 21.2 c/s. In this case the coefficients are plotted against the distance between the seismometers. The seismometers used are of horizontal type and are placed so as to be sensitive in the direction perpendicular to the line  $PQ$ . Accordingly the autocorrelation curves shown in Fig. 21 correspond to the azimuthal component. If such a polarized wave as found in the horizontal motion along the line segment  $QR$  is also predominant in this case, the form of the curves in Fig. 21 must coincide with that of  $J_0(x) - J_2(x)$ . This coincidence, however, is not well established, perhaps due to the horizontal heterogeneity of the surface soil.

The most striking fact revealed by this measurement is that the general trend of the curves or the distance giving their first zero is almost independent of the frequency. This fact reminds us the type  $D$  illustrated in the preliminary discussions. But to be consistent with the existence of wave of type  $A$  at a near place, it may be more natural to attribute this fact to the effect of hard surface soil and to assume an anomalous dispersion in which the wave velocity increases almost proportionally to the frequency of vibration.

The autocorrelation coefficients of vertical motions having frequencies of 7.0 and 13.6 c/s are plotted against the distance in Fig. 22. Although the curve for the frequency 13.6 c/s indicates the existence of waves having shorter wave lengths, the general trend coincides with that for the fre-

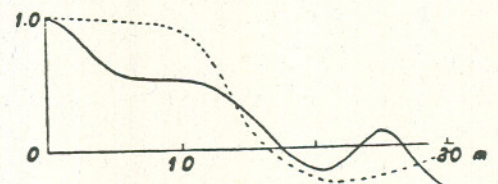


Fig. 22. Autocorrelation coefficients of vertical motion along the line  $PQ$  for

$\omega_0 = 13.6$  c/s ————,  
and  $\omega_0 = 7.0$  c/s ————.



quency 7.0 c/s, also showing an anomalous dispersion.

From the comparison between the curves for the horizontal motions and those for the vertical motions, it can be seen that the velocity of the latter is notably larger than that of the former, and this is the very fact observed along the line segment *QR*.

#### 9. Unusual behavior of vibration of 6.0 c/s on a storm day

On March 9, 1957, when it was stormy due to a low pressure passing near the east coast of Japan, filtration and correlation analyses were applied to the vibrations of two horizontal seismometers placed at the points *S* and *T* in Fig. 9. The range of the resonator frequency was from 5.5 to 10.0 c/s. The correlation coefficients obtained are plotted in Fig. 23 against the frequency of the resonator.

The dotted curve in Fig. 23 indicates the correlation observed on a calm day. The coincidence of these two curves is fairly good in the frequency range higher than 7.5 c/s, but the value of correlation coefficient for the storm day at the frequency 6.0 c/s amounts to more than 0.9, while that for the calm day is below zero. This high value was unexpected, for the distance between seismometers is about 14 m which is long enough for a considerable decrease of correlation with respect to vibrations having higher frequencies than 5.0 c/s. Also this fact is interesting because the frequency of 6.0 c/s is just twice as large as the most predominant frequency of microtremors at this place, and it suggests to us a possibility that the vibration of type *B* mentioned in the preliminary discussions might be generated under some circumstances. Further study of this problem is being prepared.

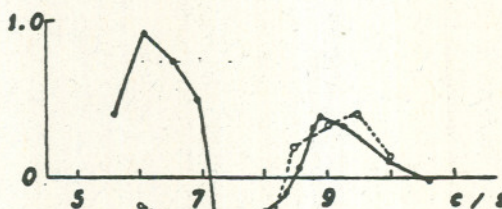


Fig. 23. Comparison of correlation curves measured on a storm day and a calm day.

#### 10. Discussions and summary

The application of our method to the microtremors has satisfactorily revealed the nature of microtremors in the frequency range higher than 5.0 c/s, and yielded the following results.

1. In the horizontal motion of microtremors a perpendicularly po-

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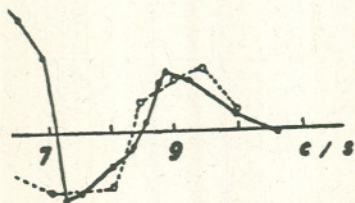


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on a storm day

to a low pressure passing  
correlation analyses were  
ismometers placed at the



Comparison of correlation curves  
on a storm day and a calm day.

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6.0 c/s amounts to more  
or zero. This high value  
ismometers is about 14 m  
ease of correlation with  
less than 5.0 c/s. Also this  
6.0 c/s is just twice as  
microtremors at this place,  
vibration of type B men-  
e generated under some  
is being prepared.

Microtremors has satisfactory  
frequency range higher

Microtremors a perpendicularly po-

Microtremor wave is predominant. Both the horizontal and vertical motions can be regarded as having respectively a single definite velocity corresponding to a given frequency.

2. Identifying the horizontal motion as Love wave, we have obtained the velocity of  $S$  wave at various depths.

3. The vertical motion also shows a definite dispersion. But if we identify it as Rayleigh wave in a layered medium, the obtained phase velocity becomes about twice as large as that expected theoretically from the velocity of  $S$  wave at depths which is determined by the use of dispersion curve for Love wave.

4. The microtremors show a marked anomalous dispersion at a place having hard surface soil.

It may be noted that the value of velocity obtained by our method is that of the phase velocity, so that the corresponding dispersion curve indicates the local structure of medium at the place of measurement. In addition, there is no such ambiguity in our method as that encountered in the determination of travel time of surface waves by the customary method.

The results obtained in this chapter strongly show the efficiency of the present method for the analyses of complicated waves. We shall note here several ways of its application to other waves appearing in Seismology.

Our method will be most effectively applied to the microseismic waves, and will clarify its wave type, the direction of propagation, and the structure of medium at the place of measurement just in the same way as in the present study of microtremors. The location of the origin of volcanic tremors is a very interesting problem in physical volcanology and can be most easily and precisely made by the direction determination by our method. In addition, the coda part of seismic waves due to an earthquake will be another important object to be studied by our method. The investigations of this coda part will give us additional informations about the structure of medium through which the wave is propagated.

Another important problem is the location of the epicentres of very small earthquakes. The direction of wave propagation determined by the present method together with the time of  $P-S$  duration will enable us to locate epicentres from observations made at a single station.



## 11. Acknowledgment

The writer expresses his thanks to Prof. Chuji Tsuboi of the Geophysical Institute, Tokyo University for his constant guidance and encouragement as well as for his valuable suggestions made in the preparation of the manuscript. The greater part of this study was made while the writer was working at the Geophysical Institute. This work was supported in part by a Grant from the Ministry of Education.

## 22. 複雑な波動のスペクトル的研究

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ここで複雑な波動というのは、stationary stochastic wave と呼ぶべきものである。これまで地震記号は位相的な立場から主に解析されて来ているが、位相的には取扱い得ない波動も地震学の分野には数多くある。たとえば、地震波のなかの複雑な部分、脈動、常時微動、火山微動などである。こういう波動の理論模型は stationary stochastic wave と呼ぶのが適當なものであり、このような波動について、1次元及び2次元の場合、その空間スペクトルと時間スペクトルの関係を求めた。このような波の解析は、先づ sharp な filter をと出し、次に時間相関を測定するという手続きによつて最も有効に行われる。このための電子管装置を製作した。

この方法を常時微動に適用した結果次のことがわかつた。但し観測された常時微動は本郷向ヶ丘のものであり、周波数範囲は5 cps以上である。

- 1) 常時微動はあらゆる方向についてほとんど一様な強さをもつてゐる。
- 2) 上下動も水平動も、周波数を与えたと速度がほとんど1つに定まる。地震学上の狭い意味での表面波である。
- 3) 上下動も水平動も分散曲をもつ。
- 4) 水平動は主に進行方向に対し直角に振動する波から成る。つまり Love 波と見做される。
- 5) 分散曲線から地下の S 波の速度を高橋健人の方法によつて求めた。
- 6) 上下動の速度は水平動のそれの約2倍の大きさをもつ。この事実は White 等によつても経験されているが、理論的には不可解であると思われる。
- 7) 固い地表層をもつ場所で常時微動は地分散の現象を示した。速度が殆んど周波数に比例して増大する。

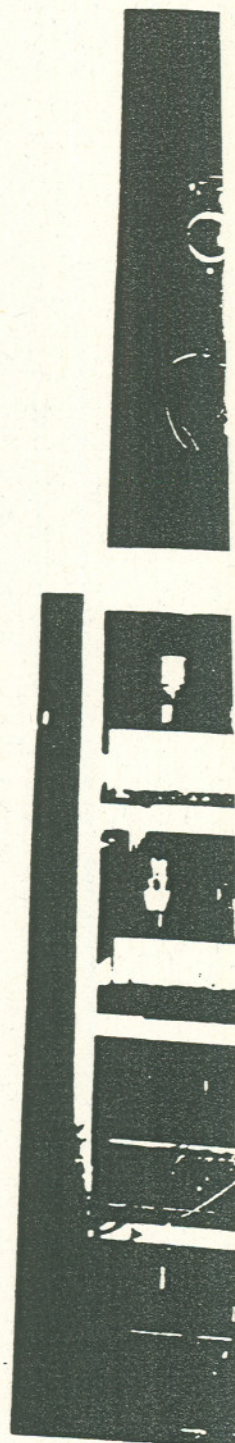


Fig. 7 Corr



Chuji Tsuboi of the Geophysical Institute. This part of this study was made in the Ministry of Education.

# 目的的研究

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地震と可変べきものである。これまで地震には取扱ひ得ない波動も地質学の分野に、常時微動、大振幅微動などである。この波動が適当なものであり、このように時間と振幅との関係を求めた。時間相関を測定するという手続き

として、観測された常時微動は、本郷向ヶ丘に設置されている。

ついで定まる。佐藤本人のいう意味

る。つまり Love 波と見做される。

ついで求めた。

この事実を White 等によつても経

した。速度が殆んど周波数に比例して

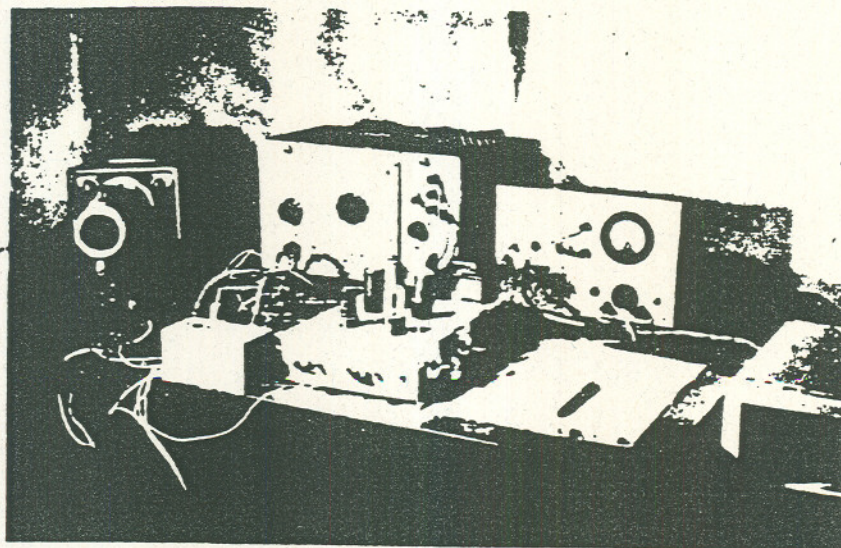


Fig. 3. Resonator and its accessories.

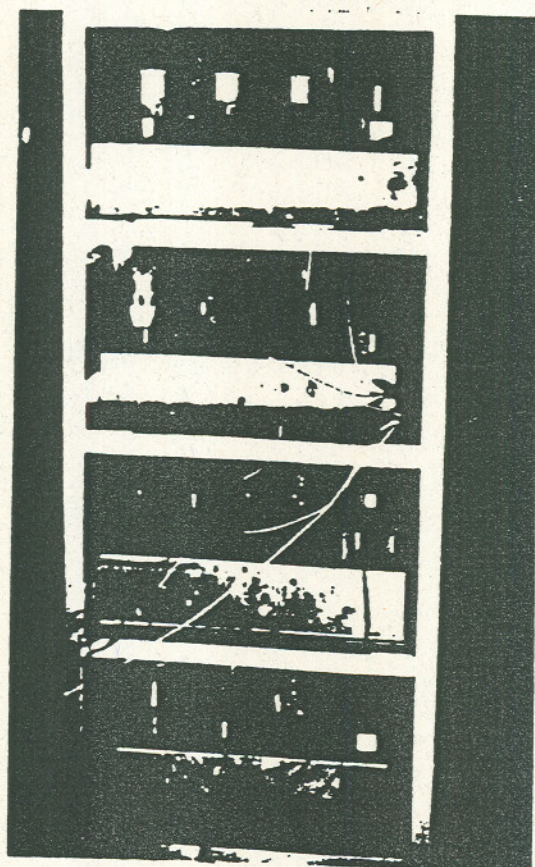


Fig. 7. Correlation computer.

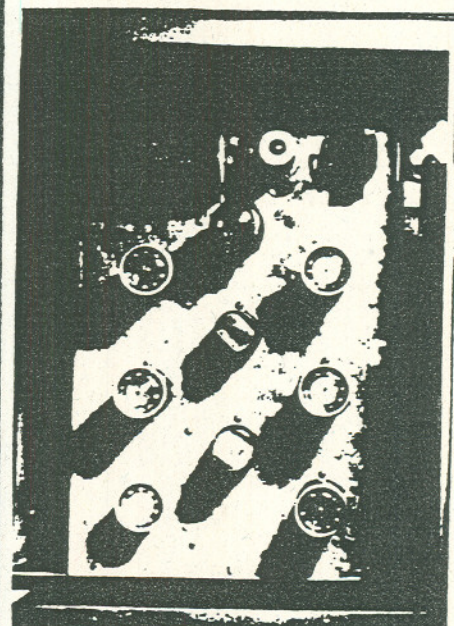


Fig. 8. Decatron indicator.