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Structure of microseismic waves: estimation of direction of approach by comparison of vertical and horizontal components

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Analysis of microseisms recorded at Kew Observatory on 8 to 10 October 1951 affords further confirmation of the wave-interference theory of microseism generation, and allows those of 8 to 10 October to be attributed to a fast-moving depression between the Azores and Iceland.

Although the bearing of the microseism-generating area changes by more than 90° during the period investigated, there is no appreciable difference in the ratio of the mean amplitudes of the north-south and east-west horizontal components as would be expected if the microseisms consisted entirely of Rayleigh waves. An investigation of the phase differences between the three components, using Lee's method, suggests that the microseisms consist of Rayleigh and Love waves in comparable proportions. Making use of this assumption, the vertical component, which is not affected by the Love waves, is correlated with the two horizontal components with an electronic correlating device, and the bearing of the microseism area can be deduced from the correlation coefficients. The calculated bearings agree reasonably well with those obtained from the meteorological charts.

The bearing of a storm on 12 to 15 November 1945, studied in a previous paper, was also calculated satisfactorily.

Introduction

Various theories have been put forward to explain the 3 to 10 s microseisms which occur with varying amplitude on records from long-period seismographs. The most satisfactory is that of Longuet-Higgins (1950), who showed that the interference between trains of waves of the same dominant period travelling in opposite directions will give rise to standing waves, below which the pressure variations do not decrease exponentially with depth like those below progressive waves, but remain finite owing to the effect of a second-order term which does not depend on depth. The two most common occurrences of such wave interference are found where waves reflected from a coast meet the incoming waves, and in the mixture of waves in the path of a fast-moving depression where the wind can change in direction by 180° in a few hours. Longuet-Higgins has shown that the pressure fluctuation on the sea bed under such conditions are of the right order of magnitude to produce the microseisms that are recorded.

It follows from this theory that the dominant microseism period should be half the dominant surface-wave period, and such an observation by Bernard (1941) and its confirmation by Deacon (1947) led to the development of the theory. Although verification of the two-to-one relationship does not fully confirm the theory, there can be little doubt of its authenticity when the changes in microseism period always follow those of the wave period (while maintaining the two-to-one ratio) at times of recording chosen so that the microseismic activity can be definitely related to particular wave conditions.

Lord Rayleigh (1885) has shown that, assuming the earth's crust to be homogeneous, surface waves can be propagated in which the displacement of the particles is partly vertical and partly horizontal in the direction of propagation. The phase differences between the two displacements is 90°, so that the resultant motion is along an ellipse contained in the plane formed by the vertical and the direction of propagation. These are now called Rayleigh waves. Love (1911) showed, however, that, when the earth's crust is assumed to be not homogeneous but to consist of a uniform layer of finite depth resting on another uniform layer of infinite depth, an additional type of wave motion is possible in which the displacement is entirely horizontal and perpendicular to the direction of propagation.

There is up to the present no clear evidence whether microseisms always consist entirely of Rayleigh waves, Love waves, or of a mixture of both. Leet (1934) concluded that the proportion of Love waves must be appreciable, while Lee (1935), working with records from Kew, concluded that they consist almost entirely of Rayleigh waves. The vertical and the horizontal east-west and north-south seismographs at Kew are so arranged that, for Rayleigh waves travelling from a direction contained in the north-west quadrant, the phase of the vertical component is 90° behind the east-west component and 90° ahead of the north-south component, the east-west and north-south components differing in phase by 180°. If the direction of approach is from the south-west quadrant the two horizontal components are in phase, both being 90° ahead of the vertical. Lee investigated a large number of records attributable to particular storms, estimating the phase differences between the three components at the minute breaks in the records and plotting these differences in the form of frequency polygons for each record. He found that, when allowance was made for the different seismograph characteristics, the most frequently occurring phase differences were generally consistent with the assumption that the microseismic waves were Rayleigh waves travelling from the direction of the supposed generating area. In another paper (1932) he showed that at Kew the ratio of the mean amplitude of the vertical component to the mean amplitude of the greater of the two horizontal components was consistent with the motion of Rayleigh waves in granite.

Object of the present investigation

The objects of the investigation described in this paper were to make a further test of the wave-interference theory of microseism generation, and to make a further attempt to find whether they consist of Rayleigh or Love waves with a view to using the microseism records to find the bearing of the generating area. If the microseisms are entirely Rayleigh waves, the ratio of the mean amplitude of the east-west component to the north-south component should give the tangent of the angle of bearing to the north. This was tested by studying records of microseisms produced by a fast-moving storm which changed its bearing from Kew by more than 90°. The example was chosen after searching through the meteorological charts for conditions in which there was only one storm that could be regarded as capable of producing the microseisms. Such a storm occurred on 8 to 10 October 1951.

Microseisms of 8 to 10 October 1951

The meteorological chart for 00.01 h 9 October 1951 showing a storm approaching the British Isles from the south-west is reproduced in figure 1, and the positions of the storm centre are marked for every 12 h from 12.00 h 7 October to 12.00 h 9 October. The storm centre moves at a speed of over 30 knots, passing west of Ireland during the afternoon of 8 October and reaching Iceland during the forenoon of 9 October. The bearing of the storm from Kew changes by about 90° from noon to noon, 8 to 9 October.

An examination of the chart shows that at all points along the path of the storm the winds veer through 180° within a few hours, and microseisms should be generated as demonstrated by Longuet-Higgins (1950). The wave and microseism records were analyzed as described by Darbyshire (1950), and the spectra of the waves and the three microseism components are shown for every 4 h in figure 2. There was a marked increase in microseism activity at Kew at 20.00 h 8 October, and at the same time the storm was rapidly intensifying and moving very fast, almost perpendicularly to the direction of the strongest wind, so that the winds in the path of the storm were changing direction by 180° within 3 or 4 h.

The dominant period of the microseisms recorded at Kew was about $7\frac{1}{2}$ s, which corresponds to a wave period of 15 s. Waves of this dominant period can only be generated where the gradient wind is more than 60 knots (Darbyshire 1952), and examination of the isobars in the meteorological charts for 24.00 h 8 October indicate a gradient wind of over 70 knots. The longest waves produced by winds of this speed are known to have a period of over 20 s, and swell of this period was in fact observed at Perranporth at 12.00 h 9 October. Some of the microseismic activity at Kew might be due to this swell being reflected off the coasts of the British Isles, but since the arrival of the swell was not accompanied by a significant increase in microseismic activity, it is reasonable to assume that most of the microseisms were generated by wave interference in the distant storm area.

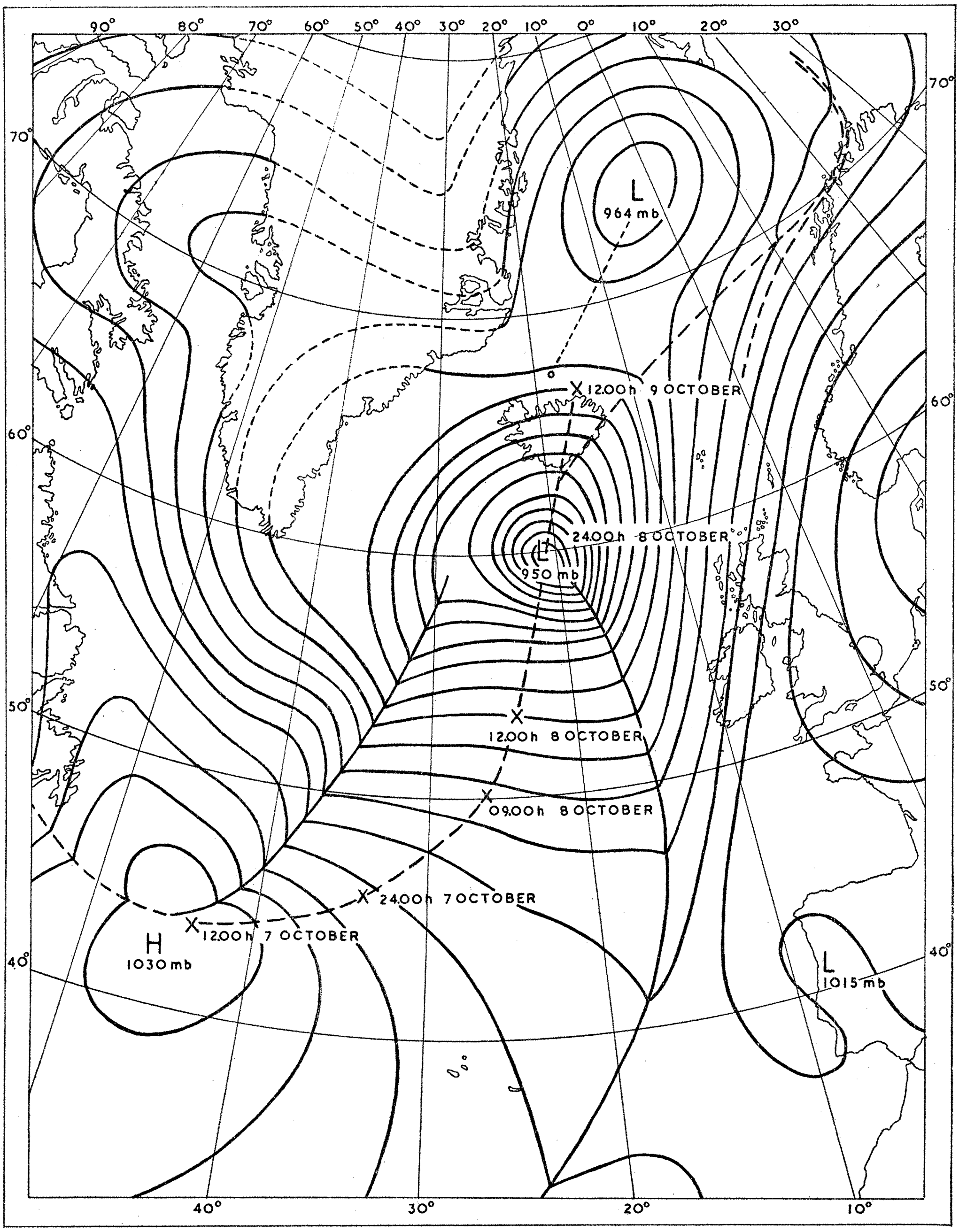

FIGURE 1. Track of the storm which produced the microseisms of 7 to 9 October 1951.

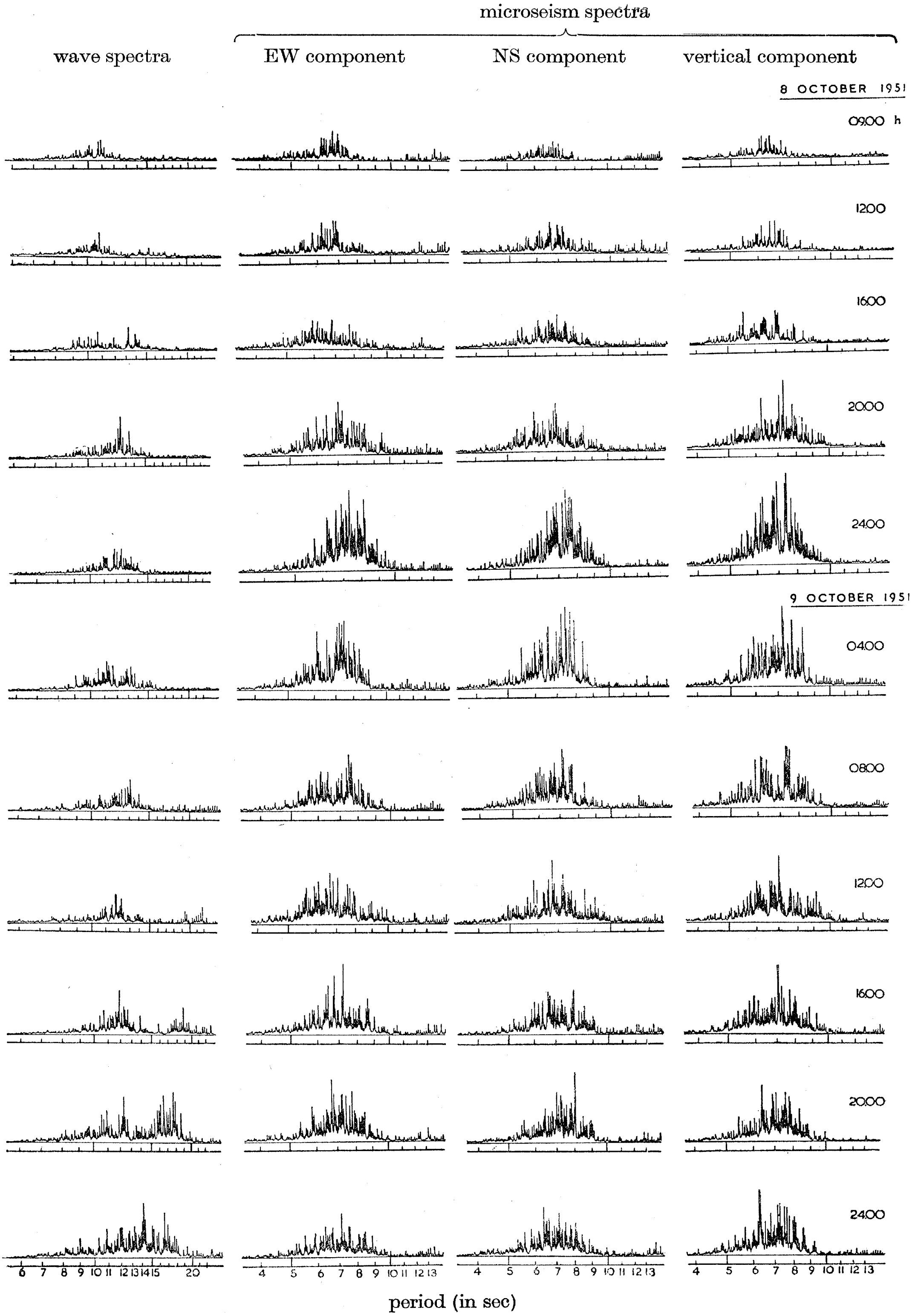

FIGURE 2. Spectra of waves and microseisms recorded simultaneously.

The amplitudes of the horizontal and vertical microseisms were found from the Fourier analyses of the records by squaring and adding all the harmonics and taking the square root of the sum, allowance being made for the different sensitivities of the seismographs. The amplitudes of the two horizontal components from 09.00 h 8 October to 24.00 h 9 October are plotted against each other in figure 3*a*, the vertical component is plotted against the north-south component in figure 3*b*, and the vertical component against the east-west component in figure 3*c*. The graphs show that the three components are always nearly equal. Since the observations are made throughout a period in which the bearing of the storm changes from west-south-west to north-north-west, it appears that there is no systematic variation as the bearing of the storm changes. The ratio of the east-west to the north-south component remains approximately 0·8, vertical to north-south component 0·8 and vertical to east-west component 1·0.

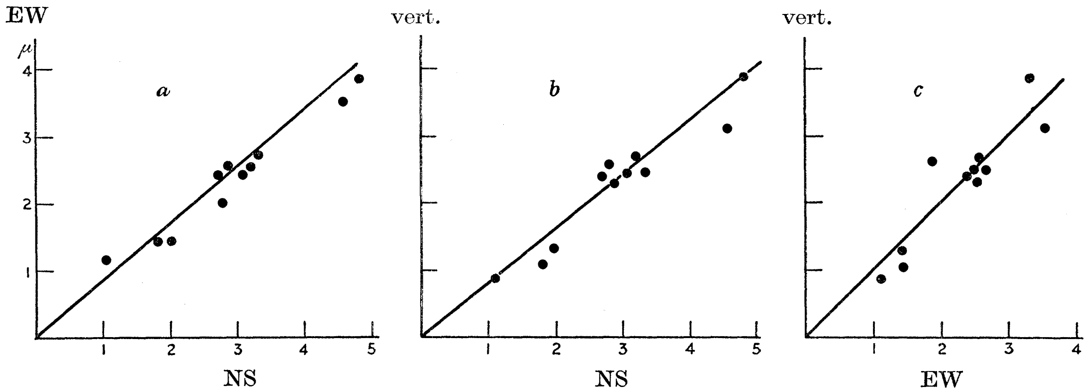

FIGURE 3. Variation of microseism components.

RELATIVE PHASES OF THE VERTICAL AND HORIZONTAL COMPONENTS

The phases of the microseisms were investigated first by using Lee's method of estimating the phase differences at the minute breaks as accurately as it can be done from the complex record. One hour's record was used for each determination. The measured phase differences were corrected to allow for the differences in instrumental characteristics which were such that, when all three components appeared to be in phase, the vertical was 45° ahead of the north-south and 30° ahead of the east-west. The corrected phase differences were grouped into intervals of $22\frac{1}{2}°$, and the numbers in these groups were smoothed by using the simple binomial expression $\frac{1}{4}(x_{n-1}+2x_n+x_{n+1})$, where x_{n-1}, x_n and x_{n+1} refer to the numbers obtained in three consecutive groups. This method of smoothing was used by Båth (1949) and is somewhat simpler than Lee's method. The smoothed numbers are plotted as frequency polygons.

The records were examined for four different positions of the storm. Three records of microseisms generated by storms on 13 November 1945, 22 October 1945 and 15 March 1945, studied in a previous paper (Darbyshire 1950), were also considered. The last two examples have been shown to be representative of microseisms generated by swell reaching the coast of the British Isles. The bearings of the

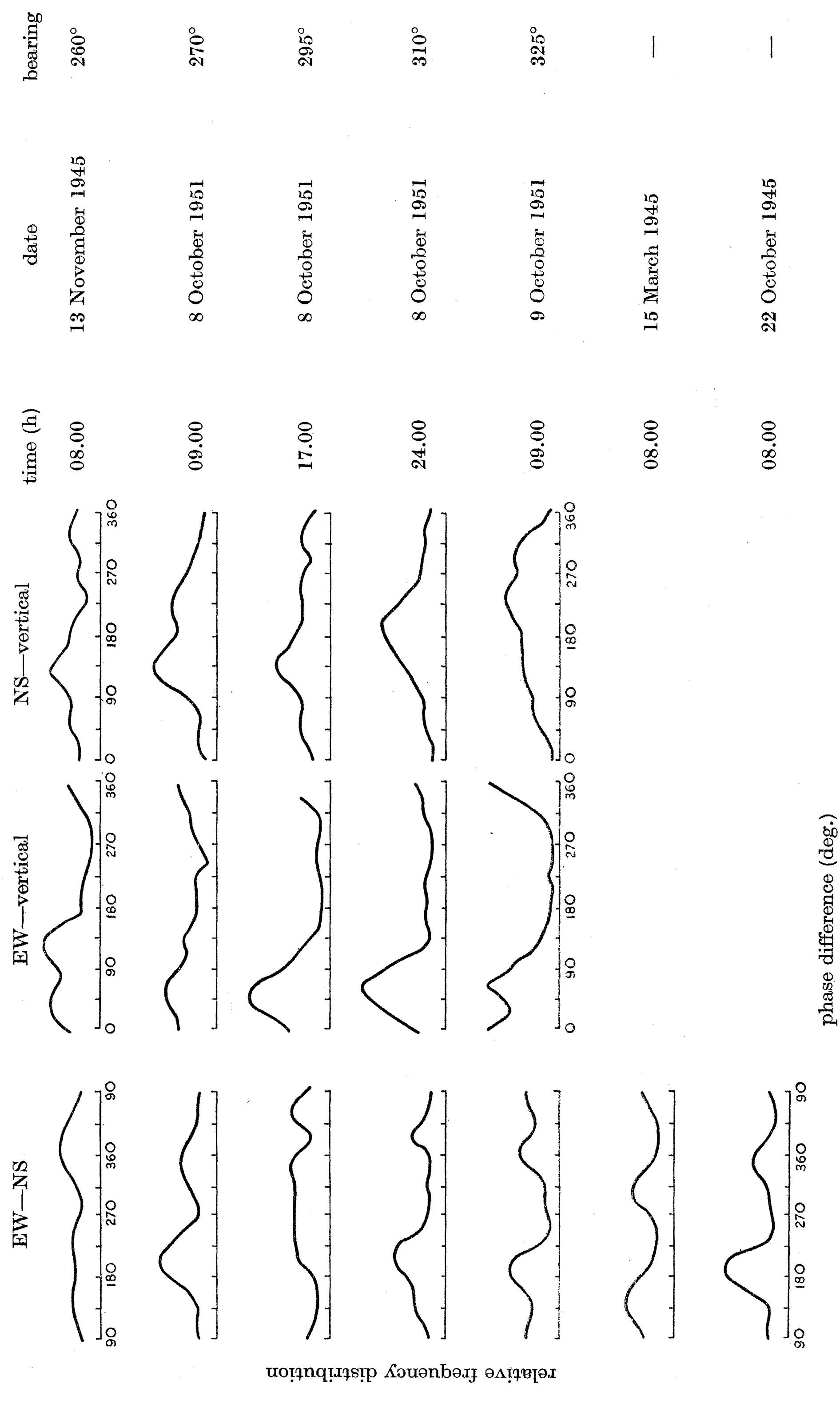

FIGURE 4. Frequency distribution of phase differences between the three microseism components (east-west, north-south and vertical).

generating areas varied from 250 to 330°. The frequency polygons of the phase differences estimated by Lee's method are shown in figure 4. The horizontal scale represents the phase differences, grouped into intervals of $22\frac{1}{2}$°, and the vertical scale gives the number of times the corrected phase differences during one hour's record fall into each group. Rayleigh waves coming from a direction between 270 and 360° would have the phase of the vertical component 90° behind the east-west and 90° ahead of the north-south, the two horizontal components differing by 180°, whilst Rayleigh waves coming from a direction between 180 and 270° would have the two horizontal components in phase, both being 90° ahead of the vertical component. The bearings of the storm are noted.

Discussion of results

The phase differences between the vertical and east-west components are reconcilable with the theoretical values for Rayleigh waves coming from a westerly direction. The most common phase difference shown in the diagrams is 45 to 67°, but the difference of this value from 90° lies within the range of error attributable to inaccuracies in the corrections for seismograph characteristics as worked out by Lee (1935). The phase differences between the vertical and north-south are more scattered, but the most common value appears to change from 135° for a bearing of 260 to 270° (09.00 h 8 October 1951 and 08.00 h 13 November 1945) to 247° for a bearing of 325° (09.00 h 9 October 1951). This seems to be a significant change outside the limits of experimental error.

The indication of the presence of Rayleigh waves obtained by investigating the phase differences appears therefore to be more promising than that obtained by investigating the amplitudes. An explanation of this difference may be found in the frequency distributions of the phase differences between the two horizontal components in which there are some indications of two modes at about 0 and 180°. This phase distribution cannot be due to Rayleigh waves coming from two different sources since there was only one storm acting at the time, and neither is there any similar indication with the vertical east-west and vertical north-south distributions; but it could be due to the presence of Love and Rayleigh waves in comparable proportions, since the horizontal displacement of a Love wave is perpendicular to the direction of propagation and therefore to the horizontal displacement of a Rayleigh wave from the same source.

If the displacement due to Rayleigh waves is given by $R(t)$, that due to Love waves by $L(t)$, and θ is the bearing to the north,

then the east-west displacement $\propto \quad x = R(t)\sin\theta + L(t)\cos\theta,$ (1)

and the north-south displacement $\propto y = R(t)\cos\theta + L(t)\sin\theta,$ (2)

the r.m.s. value of $x = \bar{x} = \sqrt{[\overline{R(t)}^2 \sin^2\theta + \overline{L(t)}^2 \cos^2\theta]},$

the r.m.s. value of $y = \bar{y} = \sqrt{[\overline{R(t)}^2 \cos^2\theta + \overline{L(t)}^2 \sin^2\theta]},$

where $\overline{L(t)}$ and $\overline{R(t)}$ are the r.m.s. values of $R(t)$ and $L(t)$, $R(t)$ and $L(t)$ being assumed to be completely independent. Then

$$\bar{x} \doteqdot \bar{y} \quad \text{if} \quad \overline{R(t)} \doteqdot \overline{L(t)}.$$

This would explain the negative results found with the amplitudes and would also agree with Lee's finding that the ratio of the mean vertical amplitude to the mean amplitude of the greater of the two horizontal components is equal to the theoretical value for Rayleigh waves in granite. If the microseisms had consisted entirely of Rayleigh waves, the ratio of the vertical component to the square root of the sum of the squares of the mean amplitudes of the horizontal components would have been the logical ratio to use.

A comparison of the frequency spectra of the vertical and horizontal components shows that there is no significant difference between them, and therefore the Love and Rayleigh waves must have similar frequency spectra. The mechanism put forward by Longuet-Higgins would determine the period of both types of microseism, but it is unlikely that Love waves would be produced directly by this method, and it is probable that the microseisms start off as pure Rayleigh waves but that a large proportion are converted into the Love kind owing to passage through faults in the earth's crust and similar causes. As the periods are the same, the speed of travel of the two types of wave would thus be different, and those arriving at Kew simultaneously would not have been generated simultaneously but the times of generation would only differ by 1 h or so; there would be very little difference in sea conditions over this period, so that the frequency range of both types of wave would be similar.

This hypothesis of the co-existence of Rayleigh and Love waves explains the greater scatter on the vertical north-south phase difference distribution diagram compared with the vertical east-west, as most of the examples involved storms where the bearing was between 225 and 315° where the proportion of Love waves, which are uncorrelated with the vertical, would be greater in the north-south component than in the east-west component. It would thus appear that a comparison of the correlation between east-west and vertical and north-south and vertical would give the direction of approach of the microseisms, and methods of doing this will now be considered.

Estimating the direction of approach of microseisms

The horizontal displacements are expressed by equations (1) and (2) above. The vertical displacement in a Rayleigh wave has a constant ratio to the amplitude of the horizontal displacement, but there is a phase shift between them which should be 90° in the ideal case. If this phase shift is taken to be ϵ, then the time lag or advance would be given by $t_0 = (\epsilon/2\pi)\,T$, where T is the period. Over a range of periods this time lag or advance will not be constant, but if the spectrum is fairly narrow and if T_m is the mean period of the spectrum, then no great error is introduced by assuming a constant time lag or advance of $(\epsilon T_m)/2\pi = t_0$ for all periods. Whether this time difference is a lag or an advance will depend on the direction of approach of the microseisms. The horizontal components at time t are correlated with the vertical component at time $t+t_0$, where t_0 may be positive or negative. Accordingly, the vertical component

$$V \propto z = k[R(t-t_0)], \tag{3}$$

where k is a constant. Thus the correlation coefficient between east-west at t and V at $t+t_0$

$$r_{xz} = \frac{k\overline{R(t)^2}\sin\theta}{k\sqrt{[\overline{R(t)^2}]}\sqrt{[\overline{R(t)^2}\sin^2\theta+\overline{L(t)^2}\cos^2\theta]}}$$

$$= \frac{\overline{R(t)}\sin\theta}{\sqrt{[\overline{R(t)^2}\sin^2\theta+\overline{L(t)^2}\cos^2\theta]}}. \tag{4}$$

Similarly the correlation coefficient between north-south at t and V at $t+t_0$

$$r_{yz} = \frac{\overline{R(t)}\cos\theta}{\sqrt{[\overline{R(t)^2}\cos^2\theta+\overline{L(t)^2}\sin^2\theta]}}, \tag{5}$$

and the correlation coefficient between the two horizontal components

$$r_{xy} = \frac{[\overline{R(t)^2}+\overline{L(t)^2}]\cos\theta\sin\theta}{\sqrt{[\overline{R(t)^2}\sin^2\theta+\overline{L(t)^2}\cos^2\theta]}\sqrt{[\overline{R(t)^2}\cos^2\theta+\overline{L(t)^2}\sin^2\theta]}}. \tag{6}$$

If $\overline{L(t)} = \overline{R(t)}$, then $\tan\theta$ is determined directly from the ratio of (4) to (5). If this assumption is not made, then from (4), (5) and (6)

$$\frac{r_{xy}}{(r_{xz}r_{yz})} = \frac{[\overline{R(t)^2}+\overline{L(t)^2}]}{\overline{R(t)^2}},$$

so that

$$\frac{\overline{L(t)^2}}{\overline{R(t)^2}} = \frac{r_{xy}}{(r_{xz}r_{yz})} - 1; \tag{7}$$

also from (4) and (6)

$$\frac{r_{xz}}{r_{yz}} = \frac{\tan\theta\sqrt{[\overline{R(t)^2}\cos^2\theta+\overline{L(t)^2}\sin^2\theta]}}{\overline{R(t)^2}\sin^2\theta+\overline{L(t)^2}\cos^2\theta}. \tag{8}$$

From (7) and (8)

$$\left\{\frac{r_{xy}}{(r_{xz}r_{yz})}-1\right\}\tan^4\theta+\tan^2\theta\left[1-\left(\frac{r_{xz}}{r_{yz}}\right)^2\right]-\left\{\frac{r_{xy}}{(r_{xz}r_{yz})}-1\right\}\left(\frac{r_{xz}}{r_{yz}}\right)^2 = 0.$$

The direction of approach can thus be found from the correlation coefficients. It should be emphasized that it has been assumed that there is no correlation between $L(t)$ and $R(t)$, but there is bound to be a certain amount of fortuitous correlation between them, particularly as they have similar frequency spectra. The effect of fortuitous correlation will be most marked if the direction is due north, south, east or west, when the proportion of Rayleigh waves in one component is very small, causing its correlation with the vertical to be small. Four examples have been considered in detail. No assumption was made initially about the equality of $\overline{L(t)}$ and $\overline{R(t)}$, and the ratio $\overline{L(t)}/\overline{R(t)}$ was found independently. The bearings found were then compared with those found by assuming $\overline{L(t)} = \overline{R(t)}$. The correlation coefficients r_{xy}, r_{xz} and r_{yz} were found by magnifying the original microseism records and reproducing them in the form of a black and white record suitable for use with the correlation meter described by Tucker (1952). In this the two records to be examined were placed alongside each other on the inside of a strip of Perspex bent to a half-cylinder. Two slits of light which could be moved relative to each other illuminated the records, one slit for each record. These slits of light were rotated quickly to scan the records several times per second, and the light output was picked up by a photoelectric cell, which thus records the sum of the variations of both records as illuminated by the slits. The output of the photoelectric cell was squared and rectified. It can be shown that variations in the output as the two slits move relative to each other are proportional to the variations of the correlation coefficient of the two records when displaced by a distance equal to the distance between the slits. The maximum correlation coefficient is taken, and the phase difference between the two records at this point determined from the distance between the slits. Using this technique, no correction was applied to allow for the difference in seismograph characteristics.

12.00 *h* 13 *November* 1945

$$r_{xy} = 0{\cdot}13, \quad r_{xz} = 0{\cdot}33, \quad r_{yz} = 0{\cdot}125,$$

$$\overline{L(t)}/\overline{R(t)} = 1{\cdot}5, \quad \tan\theta = 2{\cdot}08, \quad \theta = 64\tfrac{1}{2}^\circ.$$

Maximum correlation was obtained between V and north-south and V and east-west when the phase of both east-west and north-south were 90° ahead of the vertical (no allowance being made for seismograph characteristics). The bearing would thus be in the south-west quadrant and would then be consistent with the value of $180+64\frac{1}{2} = 244\frac{1}{2}^\circ$ N. This result compares favourably with the bearing of the storm known to produce the microseisms.

14.00 *h* 8 *October* 1951

The phase of the east-west component was shown by the correlation meter to be 90° ahead of the vertical. The north-south component was shown to be 180° ahead, and therefore it was not possible to determine from the record the right quadrant. However, the tangent of the bearing angle was calculated and the angle was compared with the position of the storm, which was known to be in the north-west quadrant:

$$r_{xy} = 0{\cdot}29, \quad r_{xz} = 0{\cdot}5, \quad r_{yz} = 0{\cdot}26,$$

$$\overline{L(t)}/\overline{R(t)} = 1{\cdot}11, \quad \tan\theta = 1{\cdot}83, \quad \theta = 61^\circ.$$

If the bearing is taken to be in the north-west quadrant it becomes

$$360-61 = 299^\circ\,\mathrm{N}.$$

24.00 *h* 8 *October* 1951

The correlation meter showed the phase of the east-west component to be 90° ahead of the vertical, and that of the north-south 90° behind the vertical. The microseisms, accordingly, come from the north-west quadrant:

$$r_{xy} = 0{\cdot}25, \quad r_{xz} = 0{\cdot}52, \quad r_{yz} = 0{\cdot}40,$$

$$\overline{L(t)}/\overline{R(t)} = 0{\cdot}45, \quad \tan\theta = 1{\cdot}97, \quad \theta = 63^\circ.$$

The bearing is thus $360-63 = 297^\circ$ N.

12.00*h* 9 *October* 1951

The east-west phase was 90° ahead of the vertical and the north-south phase was given as 180° behind the vertical, so that in this case it was not possible to determine the right quadrant. The storm is known to be in the north-west quadrant, however, and the bearing was calculated accordingly:

$$r_{xy} = 0\cdot36, \quad r_{xz} = 0\cdot43, \quad r_{yz} = 0\cdot43,$$

$$\overline{L(t)}/\overline{R(t)} = 0\cdot98, \quad \tan\theta = 1\cdot00, \quad \theta = 45^\circ.$$

Thus the bearing was $360-45 = 315^\circ$ N.

The four examples considered have given values of $\overline{L(t)}/\overline{R(t)}$ varying from 0·45 to 1·5, the mean value of all four being 1·01. Since in estimating the correlation coefficients it is impossible to exclude entirely a certain amount of fortuitous correlation, some scatter is to be expected, but the result confirms the hypothesis that for Kew $\overline{L(t)}$ and $\overline{R(t)}$ are always nearly equal. The bearings are now worked out assuming that $\overline{L(t)}/\overline{R(t)} = 1$ and are:

12.00 h	13 November 1945	250° N,
14.00 h	8 October 1951	298° N,
24.00 h	8 October 1951	307° N,
12.00 h	9 October 1951	315° N.

The bearings worked out on the assumption that $\overline{L(t)}/\overline{R(t)} = 1$ are shown in figure 5 and, compared with the position of the storm centre, are better on the whole than those calculated without this assumption. The directions of approach found for all the examples except 14.00 h 8 October 1951 were consistent with Longuet-Higgins's theory, as they indicated that the microseisms originate in the southern sector of the depression where the conditions for wave interference are more likely to be obtained. In the case of 14.00 h 8 October 1951 one would expect the microseisms to come from a more southerly direction, but as this direction is almost due west the effect of fortuitous correlation may become appreciable as the proportion of Rayleigh waves becomes very small in the north-south component.

No allowance has been made for the possible refraction of the waves as they travel from the source to Kew, and this introduces another element of uncertainty.

Conclusion

1. The relation between the period of the microseisms and the period of the swell caused by the same storm adds to the previous confirmation of Longuet-Higgins's theory that microseisms are generated by wave interference.

2. There is evidence that the microseisms recorded at Kew are composed of a mixture of Rayleigh and Love waves in approximately equal proportions.

3. Using this hypothesis of a mixture of Rayleigh and Love waves in equal proportions, it is possible to assess, at least approximately, the bearing of the area in which microseisms are being generated.

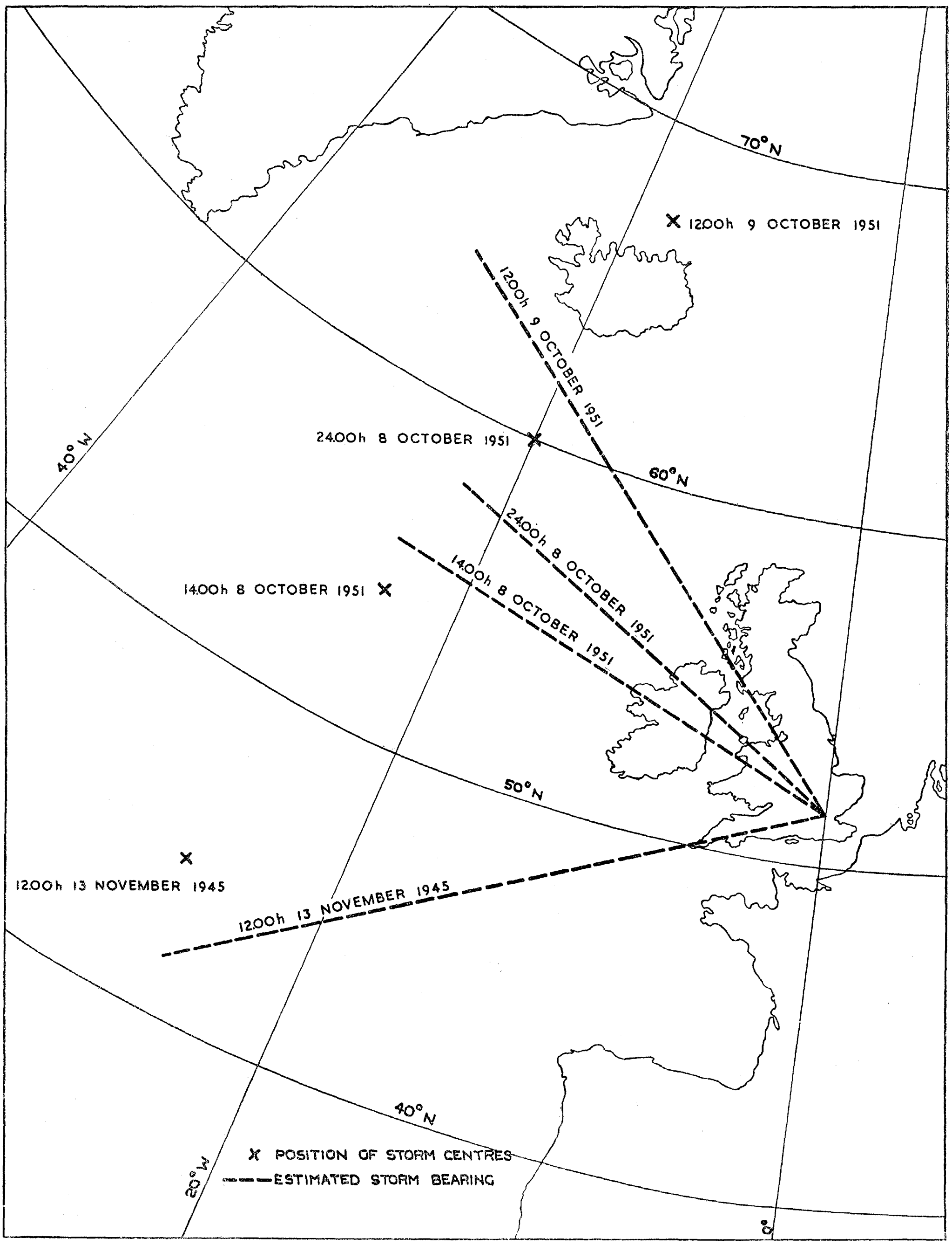

FIGURE 5. Comparison between estimated bearings of microseism-generating areas with those of the storm centre given by the meteorological charts.

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Appendix

Measurement of correlation, and relative phase of two records at maximum correlation

A detailed account of the photoelectric correlation machine used for the measurements has been given by Tucker (1952). The instrument scans the records and squares the sum of the two functions. If one function is $f_1(t)$ and the other $f_2(t+\tau)$, where τ represents the time shift introduced by displacing the records relative to each other, the output X is given by

$$X = \frac{1}{T}\int_0^{T'} \{f_1(t)+f_2(t+\tau)\}^2\,\mathrm{d}t$$

$$= \frac{1}{T}\int_0^{T} f_1^2(t)\,\mathrm{d}t + \frac{1}{T}\int_0^{T} f_2^2(t+\tau)\,\mathrm{d}t + \frac{1}{T}\int_0^{T} 2f_1(t)\,f_2(t+\tau)\,\mathrm{d}t.$$

The correlation coefficient r is given by

$$r = \frac{1}{T}\int_0^{T} f_1(t)\,f_2(t+\tau)\,\mathrm{d}t \Big/ \left\{\frac{1}{T}\int_0^{T} f_1^2(t)\,\mathrm{d}t\,\frac{1}{T}\int_0^{T} f_2^2(t+\tau)\,\mathrm{d}t\right\}^{\frac{1}{2}}.$$

The output Y, due to $f_1(t)$ alone, gives

$$\frac{1}{T}\int_0^{T} f_1^2(t)\,\mathrm{d}t$$

and Z, due to $f_2(t+\tau)$ alone, is $\quad \frac{1}{T}\int_0^{T} f_2^2(t+\tau)\,\mathrm{d}t.$

Thus $$X = Y+Z+2r\sqrt{Y}\sqrt{Z}$$

and since $$(\sqrt{Y}-\sqrt{Z})^2 = Y+Z-2\sqrt{Y}\sqrt{Z},$$

$$r = \frac{X-(Y+Z)}{Y+Z-(\sqrt{Y}-\sqrt{Z})^2}. \tag{9}$$

It is interesting to note that the line of zero correlation ($r = 0$) is given by $X = Y+Z$, and that if Y/Z lies between 0·77 and 1·3, the line $r = -1$ is within 1 % (equivalent error in the correlation coefficient) of the electrical zero.

The cross-correlograms for the three components at 12.00 h 9 October 1951 are reproduced in figure 6. The first two deflexions give the outputs Y and Z of each record separately, and the next section of record is the output from the two records combined, which varies as one record is moved relative to the other, giving X as the maximum correlation. The relative phase of the two records at the position of maximum correlation was found by repeating the correlation and stopping the machine at the maximum so that the separation δ of the two scanning lines could be measured. The paper in the correlating machine moves 1 cm, while the relative movement of the two scanning lines is 2 cm, so that if l is the separation of successive peaks on the correlogram $\delta/2l$ is a measure of the phase difference.

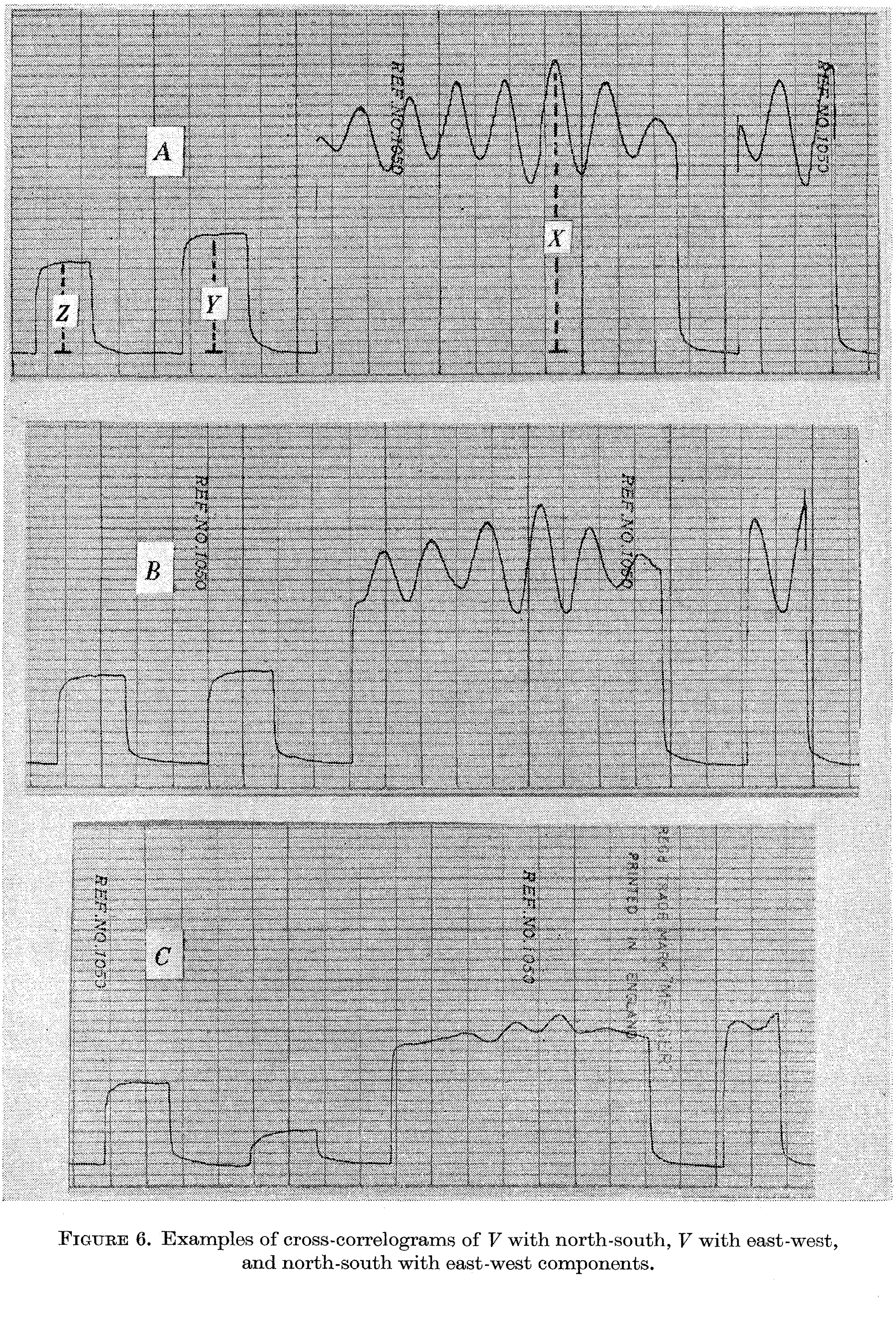

FIGURE 6. Examples of cross-correlograms of V with north-south, V with east-west, and north-south with east-west components.

The following measurements were made:

A. $Z = 8{\cdot}5$, $Y = 11{\cdot}5$, $X = 28{\cdot}5$.

$$\delta \text{ (north-south behind vertical)} = 1\,\text{cm}$$
$$2l = 2\,\text{cm},$$

whence from (9) $r_{xz} = 0{\cdot}43$, and the north-south component is 180° behind the vertical.

B. $Z = 8{\cdot}5$, $Y = 9{\cdot}0$, $X = 25$.

$$\delta \text{ (vertical behind east-west)} = 0{\cdot}5\,\text{cm},$$
$$2l = 2\,\text{cm},$$
$$r_{yz} = 0{\cdot}43,$$

and the vertical component is 90° behind the east-west component.

C. $Y = 8$, $Z = 3$, $X = 14{\cdot}5$.

$$\delta = 0 \text{ (maximum correlation at coincidence)},$$
$$r_{xy} = 0{\cdot}36.$$

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