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Recent work on microseisms in U.K.*

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1. Introduction

The study of microseisms is of great interest to the meteorologist, geophysicist and the oceanographer. But unfortunately the volume of work done at present on the subject is considerably less, even though many problems regarding their nature and origin still remain unsolved. For example, there is considerable difference of opinion between workers in U.K. and U.S.A. regarding the mechanism of generation of microseisms. Since the time when Banerji (1930) suggested that microseisms are generated by the wave field associated with storms at sea, the British workers have always looked to sea waves for an explanation of their origin. A comprehensive mathematical theory of microseism generation was put forward by Longuet-Higgins (1950) according to which the second order pressure fluctuations in standing waves which are unattenuated with depth were found to have sufficient energy to generate surface waves on the earth's crust. Such a standing wave pattern can usually be expected to occur under three different situations (Longuet-Higgins 1953).

1. In the region of the high and chaotic seas known to occur in the eye of a cyclonic depression,
2. In the wake of a moving cyclone (Fig. 1), where the group of waves generated from the side A when the storm was in position 1 encounter the group of waves generated from side B after the storm had moved to position 2,
3. When a train or progressive sea waves get reflected from a coast.

One direct result of the interference theory is that the microseisms produced should have half the period of the corresponding sea waves. This phenomenon has been observed by Bernard (1941), Deacon (1947) and Darbyshire (1950, 1954).

The American workers, especially on the Pacific side, are very critical of the stationary wave theory. In a recent survey of the British and American work (Darbyshire and Iyer 1958) it has been pointed out that it is not difficult to find out ways and means of reaching agreement.

The chief problem in the study of microseisms is to estimate the direction of arrival. This has been investigated by many workers and from time to time various techniques have been put forward. The tripartite method (Ramirez 1940, Gilmore 1946) developed by the American Navy attained great popularity during the Second World War as a promising technique for tracking hurricanes. This is an empirical method based on estimating the time differences between the same identifiable wave on records obtained from seismographs placed at the three corners of a triangle. Another empirical method was put forward by Gilmore (1953—*Operating manual for microseismic research*—see ref.) where he prepared amplitude ratio charts from a network of stations to be used for locating storms, by measuring the amplitude of microseisms recorded. It is out of place to

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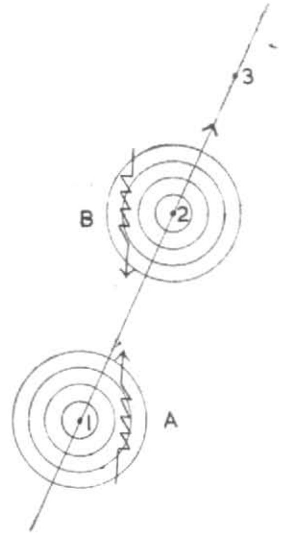

Fig. 1. Illustration of wave interference and generation of microseisms in the wake of a fast-moving depression

make a critical examination of these methods here, except mentioning that the empirical nature restricts their application to great extent.

Work in Britain was never aimed at getting an empirical method for direction finding, but for studying the nature, composition and propagation of microseisms. Even as early as the 1920s, Shaw (1917, 1920, 1921) tried to study the nature of microseisms by using suitably spaced seismographs. Lee's (1932, 1934, 1935) work on the effect of geological structure on microseismic disturbance and comparison of phases of the waves as recorded by a three-component seismograph station needs special mention.

A very promising method for the study of the composition and direction of arrival of microseisms was put forward by Darbyshire (1954). A description of this method and further development resulting in a comprehensive programme for further work on microseisms will form the rest of this paper.

2. The correlation technique of estimating the composition and direction of arrival of microseisms

If microseisms are pure Rayleigh waves it would be easy to estimate the direction of arrival at a recording station by finding the ratio of amplitudes as measured in two directions at right angles to each other. But it has been found that there is an appreciable amount of shear waves (Love waves) present. Thus in the records of a three-component microseismic station the horizontal components consist of a mixture of Rayleigh and Love waves and the vertical contains pure Rayleigh waves. The Rayleigh and Love waves may be considered independent and if the vertical component is correlated with each of the horizontal components in turn, the correlation coefficients should be a measure of the Rayleigh waves. In his method Darbyshire assumed that the Rayleigh and Love waves originate from a single source and travel in a narrow beam. He used the correlation coefficients between NS-Vertical (R_{yz}), EW-Vertical (R_{xz}) and NS-EW (R_{xy}) components for estimating the direction of arrival and Rayleigh to Love wave ratio of microseisms. The author tried to use this method for systematic tracking of microseismic sources associated with three Atlantic storms. The correlation coefficients were measured on a photo-electric Analogue Correlationmeter described by Tucker (1952). It was found that the values of R_{xy} were in general very small and the $\bar{R}/\bar{L}$ ratio as calculated using the three correlation coefficients led to erratic values. The microseismic source also did not show any striking movement with the storm centre. The results from this preliminary study (Iyer 1958) showed that any future work should investigate the following factors—

1. Nature of Love waves in microseisms,

2. Refraction in the path of propagation from the source to the recording station, and

TABLE 1

Comparison of correlation coefficients

Storm No.	R_{xz}	R_{yz}	R_r	R_l
1	0·59	0·45	0·25	0·02
2	0·77	0·44	0·32	0·02
3	0·58	0·44	0·24	0·03
4	0·77	0·33	0·25	0·07

3. The simultaneous existence of microseismic sources of different periods and their spacial distribution.

A very detailed investigation, taking all these points into consideration has been made using microseisms generated by four meteorological situations in the Atlantic. Records from the Galitizin seismographs of Kew Observatory were used. They were magnified and made suitable for analysis on the Correlationmeter. A filter was incorporated so that the behaviour of narrow bands of microseisms with one second bandwidth centred round 5, 6, 7, 8, 9 and 10 sec could be studied.

1. *Nature of Love waves in microseisms*—Nearly 1500 correlation coefficients were measured. The mean values are given in Table 1. The correlation coefficient R_{xy} has been split up into R_r and R_l which are quantities proportional to the correlation of the Rayleigh wave part and the Love wave part in the horizontal components of microseisms. The relative values of R_r and R_l affords a clear proof that the Love waves have got the nature of isotropic noise.

The fairly high values of R_{xz} and R_{yz} indicate that the assumptions regarding Rayleigh waves are correct.

It remains to see how the isotropic nature of Love waves would modify the theory for estimating the direction of arrival of microseisms. This has been worked out in detail and the following are the results, for estimating the direction of arrival (θ) and the amplitude ratio of Rayleigh to Love waves (R/L).

Love and Rayleigh waves from a single point source

$$\text{Tan}\,\theta = \left[\frac{\left(\frac{1}{R^2_{yz}} - 1\right)^{\frac{1}{2}}}{\left(\frac{1}{R^2_{xz}} - 1\right)^{\frac{1}{2}}}\right]^{\frac{1}{2}}$$

$$\frac{\bar{R}}{\bar{L}} = \left[\left(\frac{1}{R^2_{yz}} - 1\right)^{\frac{1}{2}}\left(\frac{1}{R^2_{xz}} - 1\right)^{\frac{1}{2}}\right]^{-\frac{1}{2}}$$

Love waves isotropic—Rayleigh waves from a single point source

$$\text{Tan}\,\theta = \left[\frac{\left(\frac{1}{R^2_{yz}} - 1\right)^{\frac{1}{2}}}{\left(\frac{1}{R^2_{xz}} - 1\right)^{\frac{1}{2}}}\right]$$

$$\frac{\bar{R}}{\bar{L}} = \left[\left(\frac{1}{R^2_{yz}} - 1\right)^{\frac{1}{2}}\left(\frac{1}{R^2_{xz}} - 1\right)^{\frac{1}{2}} \times \sin 2\theta\right]^{-\frac{1}{2}}$$

2. *Refraction of microseisms*—Microseisms can be affected by the variations in the geological structure of the earth's crust and the changes in ocean depth along the path of propagation. While it is difficult to estimate corrections for the former the effect due to ocean depth can be calculated. Darbyshire (1956, 1957) estimated the refraction of Rayleigh waves caused by the coupling between the ocean and the sea bed as described by Stoneley (1926). He prepared refraction diagrams for microseisms arriving at Bermuda and the British Isles. The author (Iyer *et al.* 1958) used a similar technique to draw refraction diagrams for Kew Observatory. The microseisms were assumed to originate from Kew and proceed outwards into the ocean. Using the reciprocity principle, it is possible to look for the source of microseisms along the appropriate ray path once the direction of arrival at Kew Observatory is estimated.

3. *Simultaneous existence of microseismic sources of different periods*—Using the above ideas the direction of arrival of microseisms calculated for a storm during 8/9 October 1951 (the meteorological situation and storm track are shown in Fig. 2) are plotted in Fig. 3 (a, b and c). The direction was estimated for 6, 7 and 8 sec microseisms. The results are plotted on refraction diagrams, 6 and 7 sec on the 6 sec diagram and 8 sec on the 9 sec refraction diagram. As only the direction and not the position of the microseismic source is known, it is assumed that the microseisms are generated on the storm track.

The interesting inference is that microseismic sources of different periods move more or less independently of each other. The 6 sec microseismic source shows hardly any movement at all, the 7 sec group follow the storm in the early part, and the 8 sec microseismic source shows a very rapid movement, in direct correlation with that of the storm centre.

The other storms studied are more complex in nature but in general a certain pattern reveals itself. Some of the results from this investigation are as follows—

1. In general, in the wake of a storm a composite microseismic source seems to exist. This is very obvious in the early stages but as the storm grows older the pattern becomes very complex probably owing to swell spreading over an increasingly large area.

2. The technique of filtering microseisms into narrow frequency bands and computing the direction of arrival of each band seems to be a promising way of probing into the nature of the microseismic source. In general the longer period microseisms seem to originate from nearer to the storm centre than the shorter periods.

3. In all cases the microseismic source is situated a little behind the storm centre, the "lag" depending on the history of the storm and the period of microseisms studied.

3. Rayleigh to Love wave ratio

The R/L ratio was estimated for all the storms for various periods of microseisms. One outstanding result is the dependence of the ratio on the distance of the microseismic source. In Figs. 4(a) and 4(b) the ratios for all storms studied are plotted on a bathymetric chart of the Atlantic in the actual position corresponding to the storm. The ratios for 6 and 7 sec microseisms are plotted in Fig. 4 (a) and 8, 9, 10 sec in Fig. 4(b). The distance effect is clearly shown in the figures. Of course, the data are quite insufficient to draw definite R/L contours, but the possibility is quite promising and the result indicates a possibility of estimating not only the direction but also the distance of the microseismic source by analysis of records from a single three-component microseismic station.

(It will also be interesting to study the variation of R/L ratio over continents using

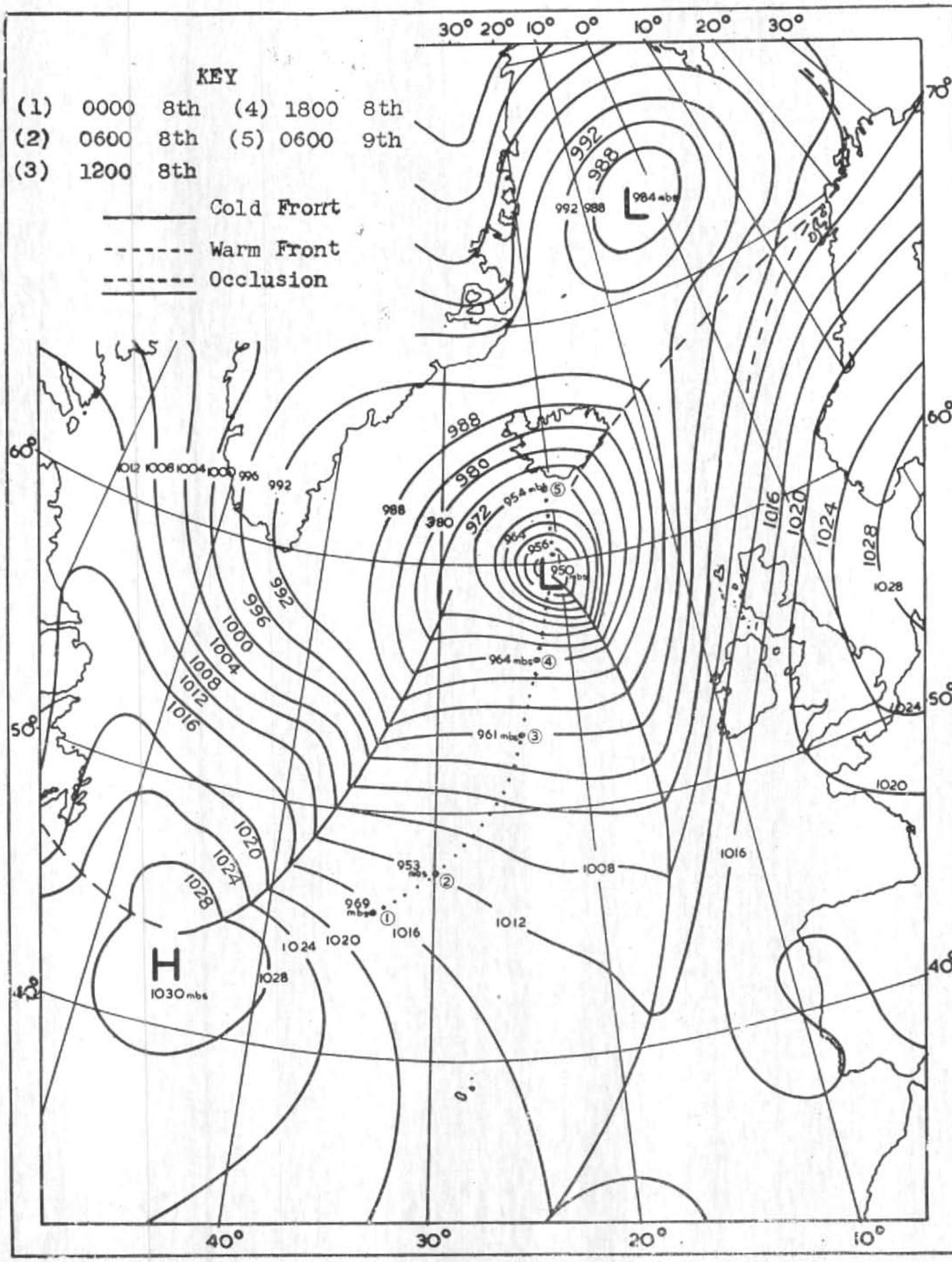

Fig. 2. Meteorological situation at 00 GMT on 9 October 1951 and the movement of the associated depression

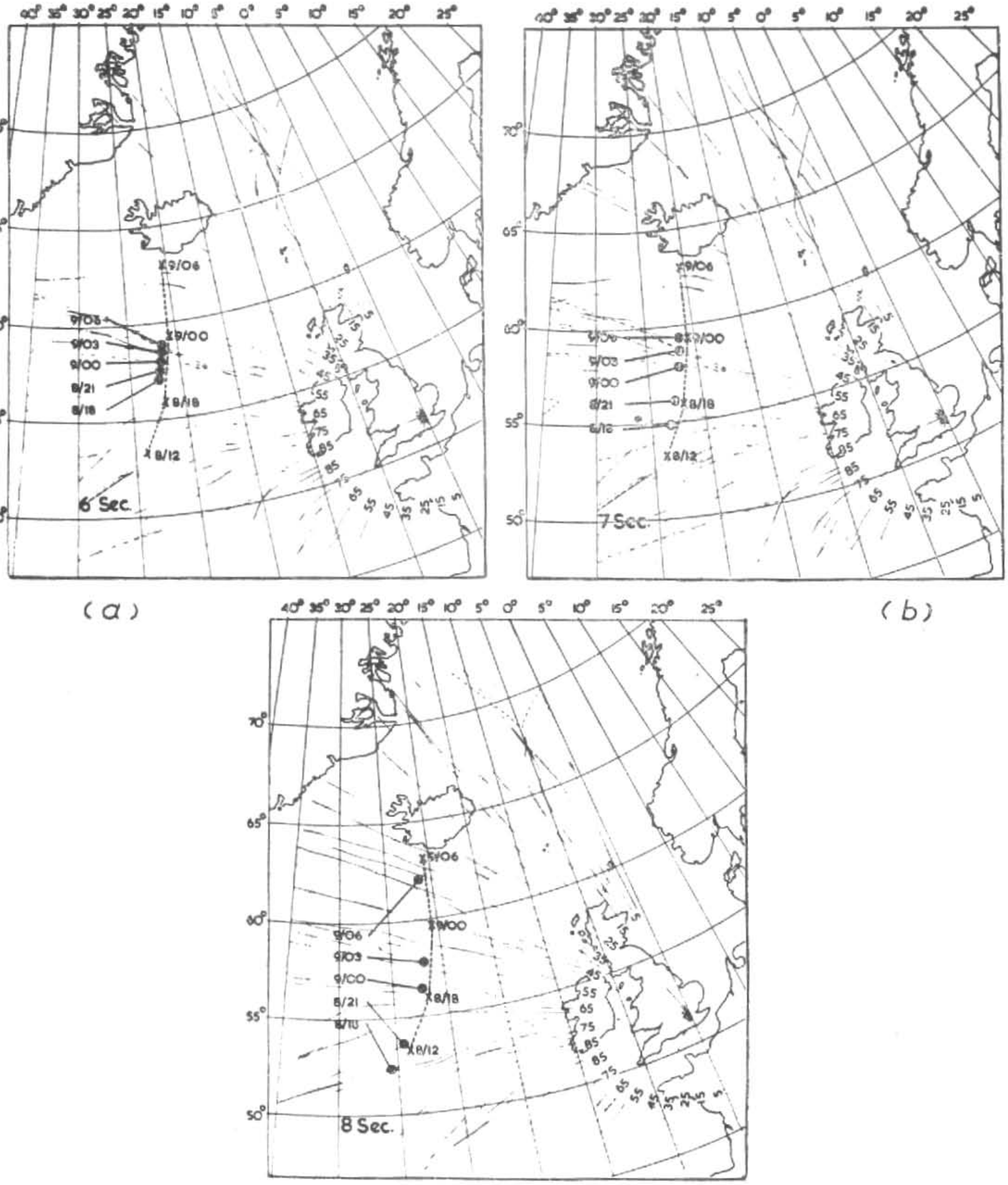

Fig. 3. Computed bearings (dark circles) of (a) 6 sec, (b) 7 sec and (c) 8 sec microseismic sources associated with the 1951 storm. The crosses show the position of the storm. Date and time are indicated

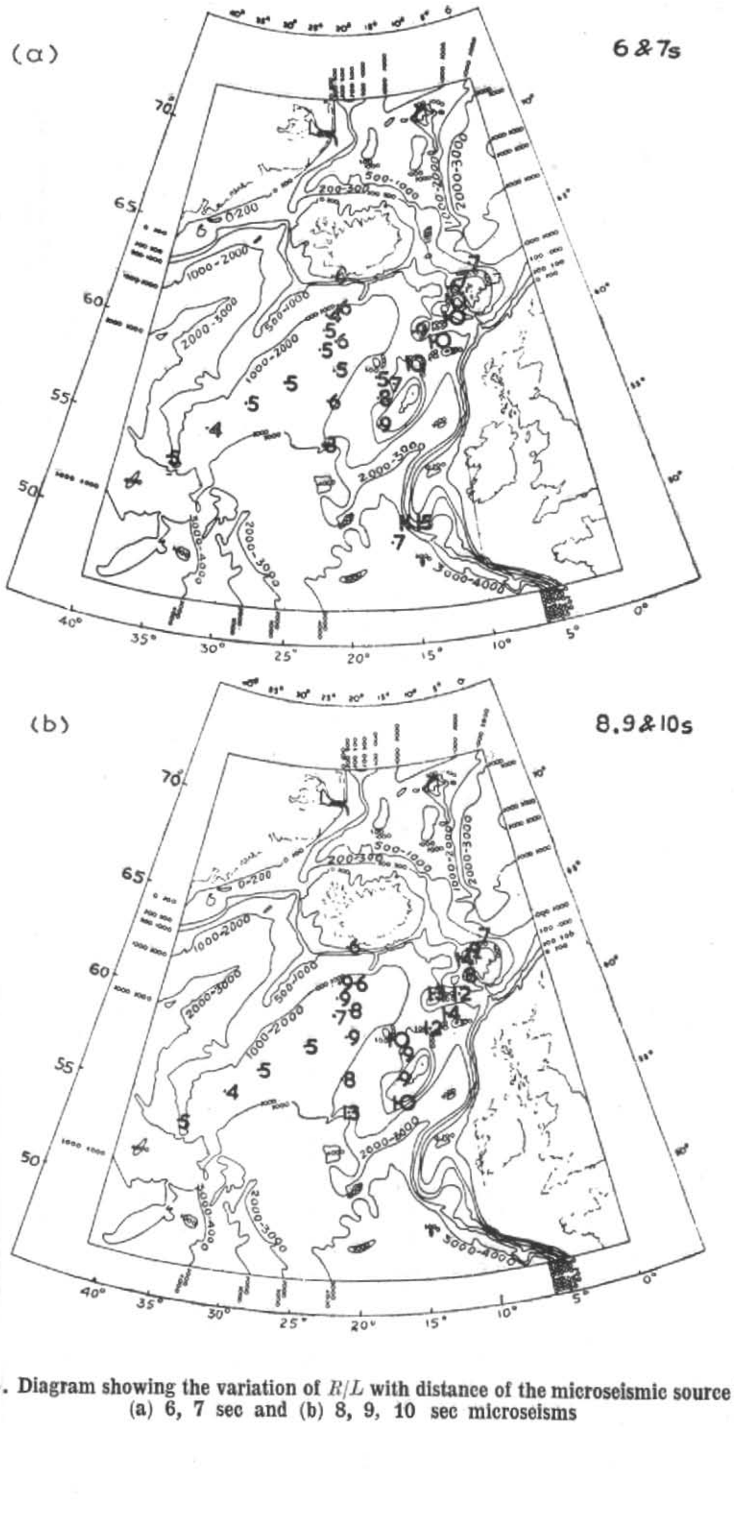

Fig. 4. Diagram showing the variation of R/L with distance of the microseismic source for (a) 6, 7 sec and (b) 8, 9, 10 sec microseisms

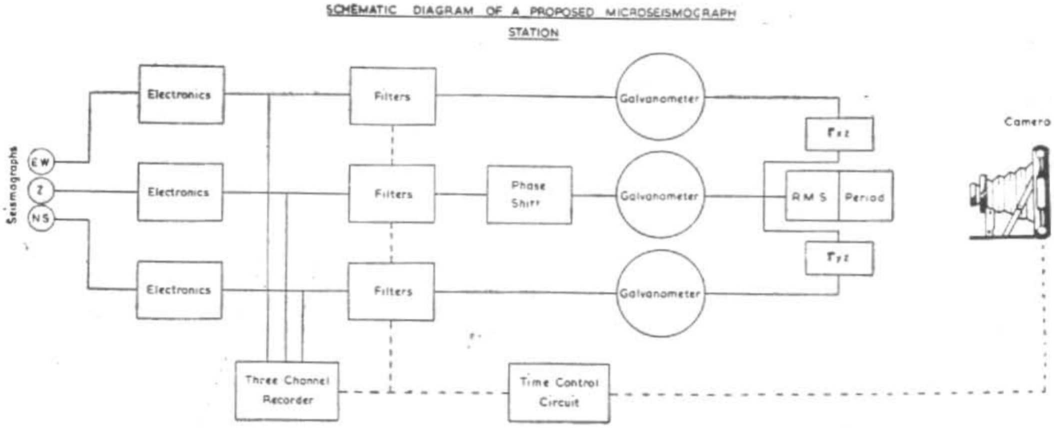

Fig. 5. Schematic diagram of a proposed automatic microseismograph station

a portable microseismic station or a network of stations where geological discontinuities are known to exist and find out whether there is any sudden change. One important application of this might be in the exploration of Antarctic ice).

4. Present programme of work

Even though study of microseisms as recorded in the past by low magnification earthquake seismographs can give valuable information from the scientific point of view, the method of analysis is long and not accurate enough. What is wanted is a system by which —

1. Microseisms can be recorded to a very high magnification,
2. A data handling system by which the information is quickly analysed direct from the seismograph signals, and
3. A diversity of meteorological situations giving good microseismic activity.

(The North Atlantic is an ideal laboratory for microseismic research from this point of view). The recent development of the Electronic Feedback Seismograph by Tucker (1958) is a very important milestone in study of microseisms. The instrument has a very high magnification up to 18000, and a flat frequency response characteristic from 1 to 10 seconds. A three-component station using these instruments is reaching completion at the National Institute of Oceanography.

A simple computing device for measuring the R.M.S. amplitude, period and correlation coefficients of microseismic waves directly from the seismograph signals is also being designed. The filtered seismograph signals are fed to galvanometers provided with a system of contacts for doing the analysis, the results being displayed on a set of P.O. counters. The completed microseismograph station will look as in Fig. 5.

5. Usefulness in India

The study of microseisms is of particular significance in India. Apart from the academic interest, the intense cyclones of the Indian Ocean, the deep fast-moving depressions of the Bay of Bengal and the heavy monsoon conditions in the Arabian Sea can provide useful data and interesting material for research. The variation of R/L ratio across the subcontinent may prove useful from the geological point of view.

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