COMPONENTS OF GEOMAGNETIC MICROPULSATIONS
IN S.W. ENGLAND

Thesis
submitted by

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Micropulsations are periodic natural fluctuations of the geomagnetic field. It is believed that their ultimate origin is to be found in the interaction between the earth's magnetic field and solar particles, which occur at the boundary of the magnetosphere. It is shown theoretically by assuming propagation as electromagnetic waves that the observed vector property of these pulsations may be affected by the geology of the observing station. The effects of certain geological situations on the varying micropulsation field are discussed.

Observatory rapid run records from three British Observatories - Hartland in Devon, Eskdalemuir in Dumfriesshire and Lerwick in Shetland - have been analyzed to examine the reported difference in the characteristic properties of pulsations observed at these places. The vector property of pulsations at the observatories were found to be significantly different. The construction of induction magnetometer used to investigate the nature of the pulsation differences is described.

Field work in S.W. England designed to search for a possible explanation of the cause of the differences in the
pulsation characteristics at the three observatories is also described. Results of the analysis of the field data are described and discussed. Among other findings, the results revealed that the in-phase and anti-phase vectors of pulsations tended to lie in a fixed plane and to possess a constant intrinsic vertical component superimposed on that attributable to the sea effect. There was also a change of period in predominant events with time of day and it was found that the plane of polarization of micro-pulsations undergoes a diurnal variation.
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CHAPTER 1

GENERAL REVIEW
1.1. Introduction

As early as 1576, Robert Norman, a London ship's instrument maker discovered that a needle perfectly balanced while non-magnetic did not remain horizontal after it was magnetized. Though the directive influence of the earth's magnetism on the compass had been used for centuries for navigational purposes, it was not until 1600 that it was realized that the earth "itself is a great magnet."

For centuries geomagnetism has been a subject of considerable study and it is now well known that the main geomagnetic field arises from sources deep within the earth and is mainly of a dipole character with surface field varying from 0.3 gauss at the equator to 0.7 gauss at the poles. The time variation of the earth's main field is apparent in the secular variation field and westward drift with periodicities which can be measured in decades and centuries.

Besides this, there are diurnal geomagnetic variations which proceed mainly according to local time known as the Solar daily (Sq) and Lunar daily (L) magnetic variations. The Lunar daily magnetic variation differs from the Sq variation in that it is controlled partly by the moon. These variations are produced by electric currents flowing in the ionosphere as a result of the dynamo action of
airflow across the geomagnetic field. The currents are greatly enhanced in a narrow strip along the sunlit portion of the magnetic equator and are known as the equatorial electrojet. At times of magnetic disturbances (D), additional currents are superimposed on the solar daily and lunar daily currents. Unlike them, the superimposed currents are strongest at high latitudes and often stronger over the night than over the day hemisphere. They are especially concentrated along the auroral zone where they are referred to as the auroral electrojets. These current systems give rise to magnetic "bays" in which the magnetic record deviates for a short time from its usual course producing a bay-like feature.

The postulation of a continuous stream of charged particles emanating from the sun and interacting with the earth's main geomagnetic field has been successful in explaining some of the most impressive perturbations of the geomagnetic field. This solar wind - as the stream is called, is electrically neutral, consisting of protons and electrons. As a result of the interaction between the geomagnetic field and the solar wind, a cavity is created in the latter within which the earth's field is confined. At the cavity boundary, now known as the magnetospheric boundary, the geomagnetic pressure is equal to the plasma
pressure. It is not difficult to imagine that the movement of this boundary caused by variations in the plasma pressure may give rise to variations of magnetic field observable on the earth's surface. Enhancement of the solar wind pressure due to solar flares and other solar phenomena is thought to be the cause of magnetic storms which are large scale perturbations of the geomagnetic field. If the enhanced emission of the sun persists for several solar rotations, it gives rise to magnetic storms which repeat over a 27-day period.

In additions to the long period and transient geomagnetic variations described above, there are at times very short period regular perturbations of the geomagnetic field that leave a characteristic pattern on the magnetogram. These regular fluctuations of the earth's magnetic field are called geomagnetic micropulsations. They have a wide spectral range from tenths of a second to tens of minutes, but in the context of this work periods of 10 seconds to three minutes are relevant. In the literature of micropulsation studies, period ranges differ considerably as they are particularly susceptible to the frequency response of the instrumentation. Amplitudes range from a fraction of a gamma \((1 \text{ gamma} = 10^{-5} \text{ gauss})\), to on rare occasions as much as a few tens of gammas.
Of course, the varying external magnetic fields give rise to induced currents within the earth, which in turn contribute to the magnetic field observed at the earth's surface. How the recorded magnetic variations can be affected by the subsurface geology will be discussed in the next chapter.

1.2 The Classification of Micropulsations.

To facilitate their description, geomagnetic micropulsations have been classified into three broad groups, though the present tendency is to split each group into a number of sub-groups.

Pc: These are continuous pulsations lasting for many hours and with periods from 2/10 secs to about 10 minutes. There is a positive-amplitude correlation with period. The average amplitude is of the order of 1/10 gamma. There may be a modulation of amplitude of Pc's, but there is no damping. The maximum occurrence frequency is during the morning hours. The 13th General Assembly of the International Union of Geodesy and Geophysics (IUGG) set up at Berkeley, California, in August 1963, commissioned a working group in a working group in the International Association of Geomagnetism and Aeronomy (IAGA) to consider the classification of geomagnetic micropulsations. According to its recommendations, Pc micropulsations are now subdivided
into the following subgroups according to their periods (JACOBS et al., 1964).

<table>
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<th>Period range in secs</th>
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<tr>
<td>Pc1</td>
<td>0.2 - 5</td>
</tr>
<tr>
<td>Pc2</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Pc3</td>
<td>10 - 45</td>
</tr>
<tr>
<td>Pc4</td>
<td>45 - 150</td>
</tr>
<tr>
<td>Pc5</td>
<td>150 - 600</td>
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Pt: These pulsations which occur mainly in the night hemisphere are series of oscillations which often do not last more than one hour. Unlike pc they are well damped transient oscillations: each series lasts from about 10 minutes to 20 minutes. They are several tenths of a gamma in amplitude and with periods in the range of 40 - 150 seconds. Accompanying pt are often small amplitude fluctuations with periods less than 40 seconds. Pt's themselves often precede or accompany a bay disturbance. Committee 10 of the IAGA recommended that pt's be subdivided into the following sub-groups.

<table>
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<th>Notation</th>
<th>Period range in secs</th>
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<tr>
<td>Pi1</td>
<td>1 - 40</td>
</tr>
<tr>
<td>Pi2</td>
<td>40 - 150</td>
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Pg: Giant pulsations are series of pulsations with amplitudes of a few tens of gamma, appearing in and near the
auroral zone. Their period is up to several minutes and the duration is of the order of one hour or more.

Giant pulsations will not be discussed further in this work since they rarely appear at the latitudes of this investigation. Because of the different instrumental sensitivity and chart speeds required to record the different groups of micropulsations it is not easy experimentally to study in detail the characteristic features of all micropulsations groups with one instrumental arrangement. In this research only pc3, pc4 and pi2 were measured and studied. Pc micropulsations will be used loosely to refer either to pc3 or pc4 or both, while unqualified "micropulsations" will be understood to stand for both pc and pt. Similarly, pt as used in the text refers exclusively to pi2.

1.3 Time Characteristics.

(1) **Diurnal variation**

A pronounced daytime maximum for pc's and a night-time maximum for pt's are two of the few characteristics of pulsations on which all observers agree, although even at the same station different observers do not agree on the exact time of occurrence of these maxima (CHRISTOFELL and LINFORD, 1966b). The time of maximum occurrence of pulsations seems to vary between stations. In the United Kingdom,
STUART and USHER (1966) have reported that the time of maximum activity is different at Lerwick (Shetland) and Hartland (Devon). They found that pc activity reached a maximum value at 08.00 hours at Lerwick and about 12.00 hours at Hartland. Maximum pt activity occurred at 21.00 hours at the two stations. From the analysis of records from Soviet telluric stations, TROITSKAYA (1953a, b, 1955) found that all stations showed a maximum of occurrence within a few hours of mid-day in the case of pc's; some, a few hours before mid-day; some a few hours after mid-day. Some stations, particularly in the South Pacific, showed a double peak. The existence of a double amplitude in the frequency of occurrence of pt's at Lerwick has been reported by STUART and USHER.

It appears that pc's often occur during 80% of all recording hours with high-sensitivity equipment, although there are also days when they are completely absent. The days without continuous micropulsations during the IGY-IGC constituted only 1% of the total number of days (TROITSKAYA, 1961). It is clear from the above that pc's do not seem to have a minimum amplitude level. Therefore their frequency of occurrence or activity will be related to the sensitivity of the recording equipment. A curve showing the frequency of occurrence against time of day may therefore have a
maximum because the events actually occur more often at that
time, or because a large percentage of events are above the
detection threshold at that time, or a combination of these conditions. To compare the frequency of occurrence of
pulsations at any two stations, therefore, it is necessary
that account be taken of the sensitivity of the recording
instruments. Neglect of this fact, and differences in the
method of analysis of the records are likely to be one of
the causes of contradictory observational results which are
common in the field of micropulsation studies.

There is also a diurnal variation in the period of
pulsations. This has been reported by many observers, but
there is no general agreement on the form of this period
variation. It is probable that it may depend on the
position of the observing station. The form of the period
variation observed in the United Kingdom, Sweden and
Germany is shown in Fig. 1.1. STUART (1965), observed that
in some cases an increase in the period of the predominant
continuous pulsation occurred during the course of the
forenoon at both Eskdalemuir (Scotland) and Kiruna (Sweden).
Though the "periods" of the predominant pulsation at the
two stations were different, the shapes of plots of average
pc activity against time of occurrence indicated a similar
form of period variation at the two stations, Fig. 1.1 (A).
FIG. 11. SOME EXAMPLES OF DIURNAL VARIATIONS OF PC PERIOD
(A) AFTER STUART (1965); (B) AFTER HOLMBERG (1953),
(C) & (D) AFTER STUART AND USHER (1966); (E) AFTER VOELKER (1963).
The data used by STUART was obtained with a rubidium magnetometer which is a total force instrument. Analyzing the vertical component of the pulsations monitored with an induction magnetometer between 1926 and 1927 at Eskdalemuir Observatory, HOLMBERG found that on numerous occasions spectral components which appeared at late night hours split into two spectral components early in the day and that these two components had a systematic change in period as the day progressed. This is brought out clearly in Fig. 1.1 (B). The long period component (pc4?), started early in the day with a period of 30 to 50 seconds, and got longer until the evening. The short period component (pc3?), started with a period of 20 to 30 seconds and remained sensibly constant or got slightly shorter throughout the day. It is to be noticed that STUART's variation curve corresponds to the long period event of HOLMBERG. A detailed study of the variation of period with time of day at the United Kingdom observatories has been made by STUART and USHER (1966). At Lerwick, Eskdalemuir and Hartland they found the period gradually decreased, reaching a minimum value at the time of peak activity, and then increased to a maximum around midnight. The difference between maximum and minimum periods was 10 - 15 seconds at each observatory. The variation of period for events with periods less than
100 seconds is shown in Fig. 1.1 (C) and (D) in the case of Hartland and Eskdalemuir respectively. Rubidium magnetometers were used to measure the pulsations. Since, as mentioned earlier, the time of maximum activity is different at Lerwick and Hartland it means that the time of minimum period of pulsations is different for these stations.

In Germany VOELKER (1963) has studied the daily change of the mean period of pulsations. In Fig. 1.1 (E), due to him, curves were drawn according to two hourly mean values of periods appearing in the N-S component of pulsations. Generally the period increased during the day but the details of the variation were not the same for the three stations - Wingst 54.5°N; Göttingen 52.3°N; and Fürstenfeldbruck 48.9°N. Specifically neither was the time of minimum period nor the rate of change of the period the same at any two of the stations. From Fig. 1.1 it is clear that not only do the details of period variation with time of the day seem different at different locations but also at the same station different observers' results do not agree in details. In Australia, for instance, DUNCAN (1961) found an increase of period with local time; CHRISTOFFEL and LINDFORD (1966a) found that the period was a minimum around local noon. This led to an exchange of correspondence between them (CHRISTOFFEL and LINDFORD, 1966b). They agreed that the differences in
their observation were probably caused by differences in the level of magnetic activity during the periods of data collection. This may probably be the case in view of the finding of STUART and USHER (1966) that the period of pulsations versus time of day plot was in antiphase with pulsation activity versus time of day plot. But it does not explain why the variation curves are different at the same stations when the observations are simultaneous (c.f. compare curves 1 and 2 in Fig. 1.1 B). The differences in the observational results may also be explained if different groups of pulsations have different forms of period variation as is suggested by Fig. 1.1 (B) due to HOLMBERG. If this is the case, obviously the form of period variation observed with a large amount of statistical data will depend on which of the two groups (1) and (2) in Fig. 1.1 (B) is the predominant event. It is also possible that the results are affected by the response of the recording equipment.

(2) Seasonal variation

From statistical studies on occurrence frequency of pc3 at different latitudes, SAITO (1962) found the minimum occurred during the winter. The time of occurrence of the maximum seemed to vary with latitude and sometimes from year to year. In the United Kingdom, STUART and USHER found that both pc and pt have maximum activity between July and
October. The periods of pc's were found to be shorter in summer than in winter. At times of greater activity there was a tendency for pulsations to occur earlier in the day especially for the short periods. A seasonal variation in the shape of diurnal variation curve for pt's has not been reported.

A 27-day recurrence tendency has been reported for pulsations. It is very pronounced for the short periods and this suggests a relation between the short period pulsation types and the geomagnetic activity level.

Pc and pt pulsations have been found to have both a universal time and a local time dependence. Whereas the occurrence seems to depend on universal time, the amplitude is modulated in local time (JACOBS and WESTPHAL, 1963).

1.4 Spatial Characteristics

(1) Variation over long distances

A characteristic of all pc's and pt's is that their amplitude increases with latitude, (JACOBS and SINNO, 1960b; TROITSKAYA, 1964). This remark also applies to the occurrence frequency of pc's. However, for short period pc's, the maximum amplitude occurs at comparatively low latitudes. JACOBS and SINNO (1960b) have drawn the ideal ionospheric current systems which would produce some observed pc and pt events. In each case they found that the
The centre of the current vortex was located between $50^\circ$ and $60^\circ$ latitude, which is in the sub-auroral zone.

The long period pc's are often observed simultaneously over large distances in longitude and latitude. For distances of 1000-2000 kms, the envelopes are often similar though the detailed pulsation may differ. For pc3, however, the correlation distance is fairly short.

A good deal of experimental investigation has been undertaken to enquire into the possible latitude dependence of the period of micropulsations. Up to date, there is no general agreement between different workers: there are even cases when different investigators using the same data arrive at contrasting conclusions, for example, ELLIS (1960) and DUNCAN (1961). From the analysis of geomagnetic pulsations recorded at the German observatories Wingst, Göttingen, and Fürstenfeldbruck by means of induction-coil variometers of the Grenet-type, VOELKER (1963) has noticed a systematic increase of the period of pc's with increasing geomagnetic latitude for the N-S component. The E-W component, on the other hand, showed no period changes with latitude. The latitude coverage was only $5.6^\circ$. HERRON and HEIRTZLER (1966) in the U.S.A. found no convincing evidence for the latitude dependence of pc's period from an analysis of inductium magnetometer records. The latitude coverage was
25°. STUART and USHER (1966) from the analysis of rubidium magnetometer records obtained from three United Kingdom observatories concluded that either there is a latitude dependence of the fundamental period of pc's or else the periods at each of the U.K. observatories are different harmonics of the same fundamental period. The latitude range covered was 7.9°. OBAYASHI and JACOBS (1958) concluded that there is a latitude variation of the period for pt pulsations while VOELKER (1962) did not find any. It appears there are some types of pulsations for which the period increases with latitude, and others for which there is no latitude dependence of the periods.

(2) Variation over small distances

Since the micropulsations are believed to have their source outside the earth, it must be expected that the external varying field will induce currents inside the earth. The magnetic fields due to these currents will modify the original inducing field. The degree of modification will be related to the electrical and magnetic property of the earth. Since these parameters do vary laterally and with depth inside the earth, variation of the characters of micropulsations from place to place may be expected. Although from place to place the change in magnetic susceptibility is usually small, WARD and RUDDOCK (1962)
have demonstrated how micropulsations differ in amplitude over a magnetic body.

The large conductivity contrast between the sea and the dry earth leads one to expect the intensity of currents induced in the ocean to be considerably greater than that of currents induced in the continental crustal layers. If the oceans are not very shallow compared with the skin depth of the magnetic variations, then the currents in the oceans should have some noticeable magnetic effects. One of the expected effects, (c.f. chapter 2), is the reduction in the amplitude of the vertical component. This effect has been observed on a drifting ice-island in the Arctic Ocean by Zhigalov (1960). His results clearly demonstrated that the amplitude ratio of the vertical to horizontal components of magnetic variations decreased considerably as the depth of the sea increased. In fact there was a remarkable similarity between the profile of this ratio and that of the ocean.

The effects of the currents induced in the sea on magnetic variations observed at stations on oceanic islands are found to be quite different from those observed on the floating ice-island. As the calculations by Ashour and Chapman (1965) showed, the difference can be explained in terms of the distortion of the induced electric currents in
the ocean by the island. This "island effect" has been studied by Mason (1963). He found significant differences between the vertical field traces for stations as close together as 20 kms ranging from phase differences of the order of 30° for a 24-hour harmonic to complete reversal in sign for short period events, one hour or less. Small differences were also observed in the horizontal field traces. As far as is known these effects have not been studied at micropulsation frequencies. It will not be very surprising if the effects are amplified at very short periods.

Anomalous magnetic field variations have been found and studied at many coastal stations in Australia, Japan, America, Canada, Italy and Russia. Schmucker (1964) found from observations at stations along a number of profiles transverse to the shore line in California, that the amplitude of the Z-variation increased rapidly as the coast was approached; while about 100 kms off shore on the island of St. Clement he found the amplitude of Z-variation to be considerably reduced. Schmucker concluded from a detailed analysis of his observations that the increased amplitude of the Z-variations near the coast could be explained satisfactorily by the presence of currents induced in the sea. Except in details the anomalous Z-variations at other coastal stations were similar to that studied by Schmucker. A number of anomalous
Z-variations have also been found inland. These are believed to be the effect of highly conducting regions beneath the crust of the earth.

PARKINSON (1959, 1962, 1964) has shown that during bays and similar geomagnetic variations, there is a general tendency for the vertical component to increase when the horizontal components change in a particular direction and to decrease when the change in the horizontal direction is in opposite direction. The correlation is often good enough to make the vertical change proportional to the component of the horizontal variation in that direction. The direction correlating with the maximum vertical change and the ratio of the vertical to the horizontal change are characteristics of a particular station and vary from station to station. PARKINSON found that in all the cases he studied the horizontal direction correlating with the maximum vertical change at a coastal station was always towards the ocean and more particularly towards the closest deep ocean. PARKINSON, as well as others, have shown that this effect occurs on almost all fairly straight coastlines near deep water.

Nearly all the "sea effect", "island effect" and "coastal effects" that have been studied in detail have involved geomagnetic variations of relatively long periods
- several minutes. It is not unlikely that these effects may exist, if not pronounced, at micropulsation frequencies. As far as is known, the only study of the sea effect on micropulsations has been in Canada by the Pacific Naval Laboratory. SHAND et al., (1959) have carried out a series of experiments to study the geographical distribution of micropulsations. Simultaneous recordings were made at a number of pairs of stations, one of which was a fixed base station at Albert Head on the sea coast near Victoria. Among other things it was found that the fluctuating Z-component was considerably larger at Albert Head than at inland stations. It was thought that the increased vertical field was associated with the sea-land interface. To investigate this further CHRISTOFFEL et al., (1961) operated pairs of stations of which one was fixed at the sea shore while two others were at inland sites. The delta and lower valley of the Fraser River were chosen for the area to conduct the investigation. The delta sediments are known to be about a mile deep and their seaward face, except for the river channels, is relatively uniform in section. However, the extent and degree of salt intrusion in the sediments are not known. The two stations occupied were at Abbotsford about 30 miles inland up the valley, and at Westham Island at the mouth of the Fraser delta. At each station the
vertical to horizontal amplitude (Z/H) ratios of micro-pulsations were determined. The results are shown in Fig. 1.2 which shows the variation of Z/H with signal period. Also included in Fig. 1.2 are plots of Z/H for other stations obtained at an earlier date. Curves (B) and (C) of Fig. 1.2 show the behaviour of Z/H ratios at Westham Island and Abbotsford respectively as compared to those at Victoria (A), Ralston (E) and Summerland (D). Victoria is on a rocky sea shore in a mountainous region; Ralston is on the great plains, while Summerland is far from the sea but in the midst of rugged terrain. It is to be noted that at Victoria, Z/H decreases with increasing period while the reverse is the case at Ralston and Summerland. The slope for Abbotsford is indeterminate because of the considerable scatter. But large scatter characterized all the Z/H plots. Generally, low values of Z/H are seen from these curves to be associated with inland stations. Although the low values of Z/H for Westham Island approach those found at inland stations, the shape of the curve is similar to that of Victoria. The low value for Z/H at Westham Island is explained by the postulation that Westham Island is in the midst of freshwater saturated sediments which present no sharp conductivity gradients. Since Westham Island is about five miles away from deep sea, it was concluded that the effect of the
FIG. I.2. VERTICAL TO HORIZONTAL AMPLITUDE RATIO $\left(\frac{Z}{H}\right)$ OF MICROPULSATION ACTIVITY VERSUS PERIOD (AFTER CHRISTOFFEL ET AL., 1961).
proximity of the sea on the $Z/H$ ratio was of secondary importance within a distance of five miles or less.

The above result should be interpreted with caution for the following reasons:–

1. The events used for calculating $Z/H$ ratios at all the stations were measured on different dates. As micro-pulsation activity undergoes a seasonal variation it is not unlikely that the distribution of amplitudes between the different components of the external varying magnetic field will change with season.

2. The geological conditions at the different stations are different.

3. In calculating $Z/H$ ratios, no account has been taken of phase differences between the two orthogonal horizontal components. Observations show that often the phase difference between the two components is variable. However, \textit{Weaver (1963)} has shown mathematically that the variation of amplitude of pulsations with distance from sea-land boundary should be expected. This is discussed in chapter 2.
1.5 Correlation with Other Phenomena

In his investigation of the effect of geomagnetic activity on a possible amplitude - period relationship, JACOBS (1959) found a linear relation in the plots of H/Kp and Z/Kp against period; Kp being the planetary index of geomagnetic disturbance and H and Z are respectively the horizontal and vertical components of the magnetic fluctuations. The data was obtained at Albert Head near Victoria, Canada. However, graphs of X/Kp and Y/Kp, where X and Y are the North and East components of H respectively, consisted of parts of two straight lines. The change in slope occurred at a period of 120 seconds. DUFFUS et al., (1962) found that both the amplitude and period of micropulsations are significantly or highly correlated with Kp. STUART and USHER (1966) found that pc period decreases in times of greater activity. At College, Alaska, CAMPBELL and REES (1961) and CAMPBELL and MATSUSHITA (1962) have observed a peak-to-peak correlation of the time derivative of the N-S micropulsation intensity and the luminosity fluctuations of the 3914A line of aurorae visible to them at the time. At the time of the aurorae the electron density was a maximum at 90 to 110 kms in the E-region of the ionosphere. Both phenomena were suspected to be due to electron precipitation into the polar region. YANAGIHARA (1959) has found that the
frequency of occurrence of pt's at Kakioka Observatory (Japan) is inversely proportional to the sun spot number while the eleven year variation of occurrence frequency of pc's is roughly parallel to that of the sun spot number. The above correlations need to be interpreted with caution in view of the fact that YANAGIHIRA (1957) also observed a linear relationship between frequency of occurrence of telluric pt and planetary index Kp.

1.6 The Origin of Micropulsations.

One of the most striking characteristics of the geomagnetic micropulsations phenomenon is the long chains of nearly perfect sinusoidal pc oscillations occurring mainly during the day. The regularity of the pc's compared with other geomagnetic disturbances led early workers to believe that they involved resonant oscillations of some kind. Because of some correlation of micropulsation activity with certain types of ionospheric perturbations and because there are no conceivable electrical processes within the earth's crust that can generate activity of micropulsation frequency, all investigators have sought for the origin of micropulsations in regions outside the earth. If micropulsations are due to standing waves of some sort, it is thought that the ionosphere could not be the ultimate source, at least for the long period pc's (pc3 - pc5), because of the long wavelengths involved. On the other hand, because
of the enormous dimension of the outer atmosphere, most of the attempts to explain micropulsation phenomenon have sought for its origin there.

One of the early studies of electrodynamic phenomena in the outer atmosphere was by Alfvén. If an electrically conducting fluid moves in the presence of a magnetic field, electric current is induced in it. The magnetic fields due to these currents modify the original field. The flow of current in a magnetic field produces mechanical forces which modify the motion of the medium. Thus hydrodynamic motion and electromagnetic phenomena are coupled. Alfvén (1942) showed that when there is a strong interaction between the electromagnetic and hydrodynamic phenomena, any disturbance in the medium, subject to certain conditions, will be propagated in the form of waves along the magnetic lines of force. These waves are now called Alfvén waves, after their discoverer.

Dungey (1954) studied in detail the electrodynamics of the outer atmosphere which may be described in terms of Alfvén waves, and showed that the interaction between the magnetic field and its variations and the exospheric particles, permitted the transmission of very low frequency fluctuations. He found that the system possesses certain natural frequencies of oscillation and suggests a way by which the solar wind could excite these frequencies.
It is not intended here to give the details of the mathematical treatment. Indication is only given of the approach. The starting equations are:

1. the usual electromagnetic equation
   \[ \text{Curl } \mathbf{H} = \mathbf{J}, \quad \text{div } \mathbf{H} = 0, \quad \text{div } \mathbf{J} = 0, \]
   \[ \text{Curl } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \mathbf{B} = \mu_0 \mathbf{H}, \]

2. Ohm's law for a perfect conductor moving with velocity \( \mathbf{V} \)
   i.e. \( \mathbf{E} = -\mathbf{V} \times \mathbf{B} \),

3. the basic equation of hydrodynamics with the sum of all the non-magnetic forces set to zero,
   i.e. \( \rho \frac{d\mathbf{V}}{dt} = \mathbf{J} \times \mathbf{B} \)

where \( \rho \) is the mass density of the gas (MKS units are used).

It is easy to show from these equations that
\[
\rho \frac{d\mathbf{V}}{dt} = -\mu_0 \mathbf{H} \times \text{curl } \mathbf{H}
\]

By considering the disturbance field \( \mathbf{h} \), defined by
\( \mathbf{H} = \mathbf{H}_0 + \mathbf{h} \), where the constant dipole field \( \mathbf{H}_0 \) is such that
\( |\mathbf{H}_0| \gg |\mathbf{h}| \), it is possible to arrive at the equation
\[
- \rho \frac{d\mathbf{B}}{dt} = \mu_0 \mathbf{h} \times (\text{curl curl } \mathbf{B}) \times \mathbf{H}_0 \quad \ldots \ldots \ldots \quad (1)
\]

This is the general equation for the propagation of Alfvén waves along the line of force in a non-uniform field; the wave velocity \( V_A \) being given by \( V_A = \mathbf{H}_0 \left( \mu_0 / \rho \right)^{1/2} \).

Further development in the solution of equation (1) is obtained by expanding it in spherical coordinates, \((R, \Theta, \Phi)\) and there results two coupled partial differential equations.
To decouple these equations it is found necessary to assume axial symmetry which requires any oscillation to occur in phase over the whole earth. Further difficulties arose in connection with the boundary conditions, which could not be readily stated except at the lower boundary, representing the earth's surface and the lower ionosphere which DUNGEY showed to be a good reflector. Solution of the decoupled equations gives two modes of oscillation of the outer atmosphere involving the following components of the electric field $\mathbf{E}$, velocity $\mathbf{V}$ and the disturbing magnetic field $\mathbf{h}$.

(1) $\mathbf{E}(E_R; E_\theta; 0)$; $\mathbf{V}(0; 0; V_\phi)$; $\mathbf{h}(0; 0; h_\phi)$
(2) $\mathbf{E}(0; 0; E_\theta)$; $\mathbf{V}(V_R; V_\phi; 0)$; $\mathbf{h}(h_R, h_\theta; 0)$.

The first mode defined by $h_R = h_\theta = 0$ has the magnetic vibration perpendicular to the magnetic median. It is possible to describe this mode as one in which the disturbance propagates along a line of force and to show that each surface of revolution of a line of force may oscillate independently. The two points at which a line of force intersects the earth's surface are considered to be the boundary of the vibrating system. Assuming the mass density of the plasma to be $10^{-21}$ gm/cc and a dipole field geometry DUNGEY obtained the approximate formula for the fundamental period ($T$) of the oscillation as $T = 0.6 \sec^8 \lambda$ where $\lambda$ is the latitude of the observing station. The values
calculated from this formula are shown by curve A in Fig. 1.3. This type of oscillation showing a very strong dependence on latitude is referred to as a torsional oscillation. It must be remarked that an independent oscillation of each surface of revolution of a line of force is a big idealization.

The second mode of oscillation defined by \( V_\theta = 0 \) and \( h_\theta = 0 \) has its magnetic vector confined in the meridian plane and oscillations may extend over the whole of the outer atmosphere. DUNGEY could not state the boundary conditions for this type explicitly. However, he estimates that the period of the fundamental oscillation is of the order of one hour. Strong latitude dependence of the period is not expected. This type of oscillation is now called a poloidal oscillation.

DUNGEY's treatment gives two measurable parameters which may readily be used to test whether micropulsations can be associated with any of these two modes of exospheric oscillations. The first is the dependence of period on latitude and the second is the state of polarization of the pulsations. As was described earlier, the latitude dependence of micropulsation period is still a matter of debate. WESTPHAL and JACOBS (1962) have attempted to modify the equations of toroidal oscillations, firstly by correcting
FIG. 1.3. THE CALCULATED VARIATION OF PERIOD OF THE TORSIONAL MODE WITH LATITUDE. A, AFTER DUNGEY; B, AFTER WESTPHAL AND JACOBS, FOR CONFINED DIPOLE; C, ALSO AFTER WESTPHAL AND JACOBS, FOR VARIABLE PLASMA DENSITY.
the geometrical model for the dipole field to take account of the confinement of the earth's field within a cavity, and secondly to take account of the variation of particle density in the exosphere. A spherical cavity was used and its effect was to greatly reduce the high latitude periods, a greater reduction being associated with the smaller radius of the confining sphere. With the introduction of a variable plasma density into the equation of toroidal oscillations and the assumption of a confined dipole field, an increase in low latitude periods was achieved. Fig. 1.3 shows the curves calculated by Westphal and Jacobs using the two methods, and compared with Dungey's. The radius of the confining field is taken to be six earth radii for the curve B, and four earth radii for C. The variable plasma density distribution used for the calculation was that used by Dessler (1958) in his studies on the geomagnetic field.

Several attempts have been made to find a solution for poloidal oscillations for which Dungey could not state the boundary conditions. Kato and Akasofu (1955) solved the equation for bounded regions in the atmosphere and obtained a series of discrete values for the period of oscillation. The periods depended on the assumed thickness of the ionized region of the atmosphere. Kato and Watanabe (1957a) solved the poloidal equation by means of a mathematical technique.
which avoided the specifying of boundary conditions. They found that the fundamental period is proportional to the fourth power of the radius of the outer atmosphere and to the square root of the plasma density. In general long periods were obtained. Further solutions of the poloidal equations have not provided any significant increase in explicit knowledge of the origin of micropulsations.

Most of the theoretical investigators of the origin of micropulsations have generally agreed that the most likely source of the pc's is the fluctuating pressure of the stream of solar particles in the magnetospheric boundary. But there seems to be no general agreement on how the disturbance originating at the magnetospheric boundary reaches the earth's surface. In the theory so far reviewed it was implicitly assumed that the pulsations observed on the earth's surface represent the electromagnetic component of the Alfvén waves which travel along the lines of force to the earth's surface. It is possible to regard the hydro-magnetic waves in a conducting fluid as oscillations of the magnetic lines of force materialized into strings in which the mass of the string is equal to the fluid mass per line of force. This concept gives results in agreement with the solution of the toroidal equation. Many, including JACOBS and WATANABE (1962), MATHER et al. (1964), have used this
Watanabe (1959) suggests that the variation of Alfvén wave velocity can lead to resonant oscillation in the exosphere and he believes that short period pc's may be caused by it.

A number of investigators including Jacobs and Watanabe (1962), Prince and Bostick (1964), Greifinger and Greifinger (1965), have made theoretical calculations on the wave transmission coefficient of the ionosphere and its effect on hydromagnetic waves originating in and outside it. It was shown that the ionosphere amplifies certain hydromagnetic frequencies. It was predicted that as a result of the filtering action of the ionosphere the frequency of micropulsation will be higher in the night than in the day. However, this is contrary to observations.

Some, like Kato and Tamao (1962), have attempted to explain certain types of pulsations in terms of ionospheric currents induced by the hydromagnetic oscillations of the atmosphere. Jacobs and Watanabe (1964) suggest that currents are induced in the ionospheric region somewhere in the auroral zones where an oscillating magnetic line of force passes through. The currents leak into the polar cap regions as well as into the middle and low latitude regions thus forming an oscillating current vortex, one in each of
the hemispheres. According to them, the micropulsations observed in middle and low latitudes are due to the electric currents so produced in the ionosphere.

Finally, interpretation of pulsations in terms of modulation of the ionospheric conductivity and thereby ionospheric current system have been suggested by CAMPBELL (1962), CAMPBELL and MATSUSHITA (1962) and JACOBS et al (1965). The modulation is thought to be produced by modulated energetic particle beams, which ionize the atmosphere. The energetic particles, in their turn, may be modulated by periodic perturbations of the magnetic field due to its interaction with the solar wind.

It remains to see, which of these theories fits the observations. Some of these are difficult to put under experimental test because they offer no experimentally measurable parameters.

1.7 Micropulsation Activity at Three British Observatories

In the recent years, the space research group of the Geophysics Department of Imperial College has been making an experimental study of micropulsation phenomenon. Though the general characteristics of these pulsations were examined, the main interest has been on the search for latitude dependence of the periods as predicted by theory.
Recordings have been made at Lerwick in Shetland, Eskdalemuir in Dumfrieshire and Hartland in Devon. These stations are close to the Greenwich Meridian and therefore form a good N-S traverse. Registration of pulsations at each station was made with a rubidium magnetometer which has a peculiar property of responding only to pulsations in the meridian plane (chapter 6). Since the rest of the present study is based on the results of the above investigation relevant sections of the results of the research is quoted below. Details of the study are found in the paper by STUART and USHER (1966) which has been referred a number of times.

1. Pp occurrence times are radically different at the three stations, the maximum being 08.00 hours at Lerwick and 12.00 hours at Hartland.

2. The general shape of the pp spectrum is distinctly different at the three stations. The maxima are 30 seconds at Lerwick, 60 seconds at Eskdalemuir and 40 seconds at Hartland; a secondary peak at 25 seconds occurs at Eskdalemuir.

3. There is a seasonal change of both pp and pt activity. A maximum occurs at Hartland at the autumnal equinox for both pp and pt but for Lerwick the pp maximum is in July/August and pt maximum in September/October.

4. Significant energy differences between the stations exist.
It is apparent that significant differences exist between the characteristic properties of pulsations at the three observatories. It is possible that some of these differences may be as a result of (a) differences in the geological conditions between the observatories, (b) differences in the position of the observatories relative to the micropulsation source. If this is the case then the study of the energy differences will give an indication of the spatial distribution of micropulsation source. (c) Plane of polarization of pulsations being different at the stations.

1.8 Present Work

So far there has been no experimental confirmation or modification of the existing theories of the origin of micropulsations, probably because of an insufficient statistical accumulation of data. To attempt this requires definite information regarding the period structure of the pulsations, their vector properties and phase relationships. In comparing observations with theory, it is essential that the effect of site differences on the recorded pulsations be known. Most of the experimental investigations to enquire if micropulsations may be identified with any of the two modes of oscillation of the outer atmosphere have been
designed to search for dependence of micropulsation periods on latitude. As has been discussed the results have been very inconclusive. But theory may also be compared with observations by investigating the distribution of signals among the three components of pulsations. It is surprising that very little has been done in this direction. The aim of the present work is therefore firstly to study the vector property of micropulsations and to compare the results with existing theories. Secondly to inquire whether the observed micropulsation characteristic differences between the three British Observatories are intrinsic in the micropulsation phenomenon or arise purely as a result of site differences.
CHAPTER 2

EFFECTS OF SUBSURFACE CONDUCTIVITY
CONTRASTS ON RECORDED GEOMAGNETIC VARIATIONS
2.1 Introduction

The origin of micropulsations is believed to lie outside the earth. Because the earth has a non-vanishing conductivity the varying external micropulsation field gives rise to a micropulsation field of internal origin by the process of electromagnetic induction. The micropulsations recorded on the surface of the earth are as a consequence the resultant of the inducing and induced micropulsation field. The induced field is controlled by the inducing field and by the electrical and magnetic state of the ground. Variation of these parameters from place to place may therefore be expected to give rise to variations in the characteristics of micropulsations recorded at different places.

In electromagnetic c.g.s. units, the permeability of rocks in the earth's crust does not differ much from unity, except for those rocks with a high concentration of ferromagnetic materials. But the wide range in conductivity in various rocks leads one to expect that, except in the vicinity of ferromagnetic masses where "amplification" of micropulsations occurs (WARD and RUDDOCK, 1962), the variations in the internal part of the micropulsation field from site to site will largely be due to differences in electrical conductivity.
To date, theory and observation have been unable to state categorically whether micropulsations arise from a uniform source of very large dimensions as the proponents of the plane wave model for pulsations believe, or from local ionospheric sources such as the current vortex system of Jacobs and Watanabe (1964). The comparison of observation with theory is often made difficult because of lack of knowledge of even the approximate effect of the recording site on the recorded pulsation. Price (1962) has shown that the dimensions of the source of pulsations need be taken into account in making magnetotelluric interpretations and as will be seen later the same remark applies when evaluating the effect of certain geological situations on recorded magnetic variations. In this chapter only qualitative effects of certain subsurface conductivity distributions are discussed where the source of the recorded geomagnetic variations are (a) of infinite dimensions, (b) of finite dimensions. Because of obvious mathematical difficulties only the effects of very simple geological formations are considered. Consequently the effects of geological situations on recorded pulsations are discussed more or less qualitatively.
2.2 The General Equation of Electromagnetic Induction in a Uniform Flat Earth.

The ground is considered as a semi-infinite conductor. A rectangular coordinate system \(0 x y z\) (Fig. 2.1) is chosen such that the origin is on the surface of the ground, with the ground occupying the half space \(z > 0\), and the positive direction of \(z\) is vertically downwards. The conductivity is assumed to vary only with \(z\) and the dielectric constant \(\varepsilon\) is taken to be uniform throughout. Permeability \(\mu\) is taken to be unity and electromagnetic c.g.s. units are used. It is assumed that at some height, say \(z = -h\), above the earth, there exists a varying magnetic field source. The varying magnetic field will induce currents inside the earth. The problem is to determine the resultant magnetic field at \(z = 0\). Obviously the electromagnetic fields must be governed by Maxwell's equations. The problem then reduces to finding solutions of these equations which must satisfy certain boundary conditions.

Maxwell's equations for a charge free isotropic medium are

\[
\nabla \times \vec{H} = 4\pi \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{1}
\]

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2}
\]

\[
\text{Div } \vec{D} = 0 \tag{3}
\]

\[
\text{Div } \vec{J} = 0 \tag{4}
\]
FIG. 2.1. CO-ORDINATE SYSTEM USED TO CALCULATE INDUCTION EFFECTS IN A HORIZONTALLY UNIFORM EARTH. XY PLANE REPRESENTS EARTH'S SURFACE.
where \( \vec{H} \) and \( \vec{E} \) are the magnetic and electric fields respectively while \( \vec{J} \) and \( \vec{D} \) are respectively, the conduction and displacement current densities. In an isotropic medium the following relations hold between the electromagnetic field vectors

\[
\vec{D} = \varepsilon_0 \vec{E}; \quad \vec{B} = \mu_0 \vec{H}; \quad \vec{J} = \sigma_z \vec{E}
\]

where \( \sigma_z \) is the ground conductivity and the subscript "z" is used to indicate that it varies with depth. At micropulsation frequencies it is easily shown that the displacement current density is negligible compared with the conduction current inside the earth. This means that \( \nabla \times \vec{D} / \sigma \) can be set to zero. Taking the curl of equation (2) and making use of equations (1), (4) and (5) then the equation

\[
\nabla^2 \vec{E} = 4\pi \sigma_z \frac{\partial \vec{E}}{\partial t}
\]

results. Since \( \text{div} \vec{J} = \text{div} \sigma_z \vec{E} = 0 \) it follows that

\[
\sigma_z \left( \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} \right) + E_z \frac{\partial \sigma_z}{\partial z} = 0
\]

It is possible to show that the induced currents flow parallel to the surface at all depths, i.e. \( E_z = 0 \). Thus equation (7) becomes

\[
\sigma_z \left( \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} \right) = 0
\]

Equation (6) may be rewritten in the form

\[
\left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \vec{E} = 4\pi \sigma_z \frac{\partial \vec{E}}{\partial t}
\]
In seeking the solutions of equations (9) and (8), it will be assumed that all field quantities depend on time through the factor $e^{i\omega t}$, where $\omega$ is the angular frequency. Following the method due to PRICE (1950) it is assumed that equation (9) can be solved by the method of separation of variables in which $\vec{E}$ is of the form,

$$\vec{E} = e^{i\omega t} Z(z)F(x,y)$$

i.e. the electric field is determined by three functions one of which ($Z$) depends entirely on $z$, the second ($F$) is independent of $z$ and time and the third function ($e^{i\omega t}$) is only a time factor. Since it was assumed earlier that the conductivity varies only with depth it means that $Z(z)$ is a function of $\sigma_z$. The assumption of a horizontally homogeneous earth clearly implies that $F(x,y)$ depends solely on the external source of the varying magnetic field. Use of equation (8) shows that $F(x,y)$ can be written as

$$F(x,y) = \left( \frac{\partial P}{\partial y}, -\frac{\partial P}{\partial x}, 0 \right)$$

where $P$ is a function of $x$ and $y$.

Hence $\vec{E}$ may be expressed in the form

$$\vec{E} = e^{i\omega t} Z(z)\left( \frac{\partial P}{\partial y}, -\frac{\partial P}{\partial x}, 0 \right)$$

Substituting $\vec{E}$ from equation (12) in equation (9) it is easy to show that
\[ \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \nabla^2 P = 0 \quad (13) \]

and

\[ \frac{\partial^2 \bar{Z}}{\partial x^2} = (\nabla^2 + 4 \pi \sigma_0 \omega) \bar{Z} \quad (14) \]

where \( \nabla^2 \) is the separation constant. The physical significance of this constant has been given by PRICE (1962) as being related to the dimensions of the source. Specifically \( 1/\nabla \) is proportional to the horizontal dimension of the varying magnetic field source. The solution of equation (14) is

\[ \bar{Z} = A e^{\theta_0} + B e^{\theta_0} \quad (15) \]

where \( \theta^2 = \nabla^2 + 4 \pi \sigma_0 \omega \quad (16) \)

In the free space outside the earth where \( \sigma_0 = 0 \) equation (15) becomes

\[ \bar{Z} = A e^{\theta z} + B e^{\theta z} \quad (17) \]

The magnetic field \( H \) at any depth \( z \) is easily obtained from equations (2), (12) and (13) and is given by

\[ i \omega H = -e^{i\omega t} \frac{\partial \bar{Z}}{\partial x} + \frac{\partial \bar{Z}}{\partial y} \quad (18) \]

So far no assumption has been made about the form of the functions \( P \) and \( Z \). In the rest of the chapter use will be made of the equations developed in this section and the functions \( Z \) and \( P \) will assume specific forms.
2.3 The Magnetic Field Variations Over a Uniform Earth Due to a Source of Infinite Dimension.

As noted in the last section \( \gamma \nu \) is a measure of the dimension of the source of the field variations. For a source of infinite dimension \( \nu = 0 \). For a uniform earth, \( \sigma_z = \sigma \) at all depths. Since \( Z \) cannot have an infinite value (infinite current) at very great depths equation (15) becomes

\[
Z = A_1 \exp \left( -\sqrt{4\pi i \omega \sigma} \right) z \tag{19}
\]

where \( A_1 \) is independent of \( z \). Substituting the above value of \( Z \) in equations (12) and (18) gives respectively the electric field \( \vec{E} \) and the magnetic field \( \vec{H} \) inside the earth as

\[
\vec{E} = A_1 e^{iwt} \left( \frac{\partial P}{\partial y}, -\frac{\partial P}{\partial x}, 0 \right) \exp \left( -\sqrt{4\pi i \omega \sigma} \right) z \tag{20}
\]

and

\[
iw \vec{H} = A_1 \sqrt{4\pi i \omega \sigma} e^{iwt} \left( \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}, 0 \right) \exp \left( -\sqrt{4\pi i \omega \sigma} \right) z \tag{21}
\]

i.e. \( H = A_1 \sqrt{2\pi T} \left( \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}, 0 \right) \exp (wt - i\pi /4 - \sqrt{4\pi i \omega \sigma}) z \tag{22}
\]

where \( T = 2\pi /\omega \) is the period of the variation.

The only assumption made so far is that the source of the varying magnetic field should be of infinite extent. Obviously a source of infinite size will give rise to a uniform field over the earth's surface. But equation (22) has an important implication that the vertical component of the field is always zero regardless of the ground
conductivity or the period of the varying magnetic field. Now, the observed field on the earth's surface is the vector sum of the inducing and induced fields. The zero value of the resultant vertical field may be explained if it is postulated that the induced vertical field is always equal and opposite in sign to the inducing vertical field.

If micropulsations may be regarded as a wave phenomenon originating from an infinite source, the associated waves recorded on the earth's surface must be plane. The zero value of the vertical component of both the electric and magnetic fields (equations (20) and (22)) on the ground surface implies a plane wave at normal incidence. It is not possible to draw any conclusion of the effect of the ground conductivity on the horizontal component of the variation vectors from equation (22) because $A_1$ may be some function of $\sigma$ and $w$. However, it is possible to obtain this information by treating the problem as the reflection of plane electromagnetic waves incident normally on a homogeneous earth.

It is convenient to rewrite equation (6) in the form

$$\nabla^2 \vec{E} = \frac{1}{\mu} i \sigma \omega \vec{E} = i \eta^2 \vec{E}$$

(23)

where

$$\eta^2 = \frac{1}{\mu} \sigma \omega$$

(24)

Putting $k = \omega/c$, where $c$ is the velocity of light, then
\[ \eta/k = 2c\sqrt{\frac{\pi G_0}{w}} \] is very large compared with unity at micropulsation frequencies and for average ground conductivity. For example, at \( w = 2\pi, (f = 1 \text{ c/s}), \) and \( \sigma = 10^{-13} \text{ e.m.u.} \)

\[ \eta/k = 2 \times 3 \times 10^{-10} \sqrt{10^{-13}/2} \approx 2 \times 10^4. \] At frequencies smaller than 1 c/s larger values of \( \eta/k \) are obtained. Thus it can be safely assumed that at micropulsation frequencies \( \eta/k \gg 1. \)

Let the incident wave vectors be identified by a suffix "i", the reflected wave vector by the suffix "r", and the transmitted vector by the suffix "t". If the electric vector \( \mathbf{E} \) of the incident plane wave lies along the x-axis and the magnetic vector \( \mathbf{H} \) has only a y-component then it can be shown (Stratton, 1943) that the incident, reflected and transmitted vectors can be expressed as below

\[ E_x^i = e^{-ikz}, \quad H_y^i = \frac{1}{c} e^{-ikz}, \]
\[ E_x^r = a e^{ikz}, \quad H_y^r = -(a/c) e^{ikz}, \]
\[ E_x^t = b e^{-\eta z\sqrt{i}}, \quad H_y^t = (\eta b/w\sqrt{i}) e^{-\eta z\sqrt{i}}, \]

where \( a \) and \( b \) are constants. The continuity of the fields at the ground surface requires that the following relations must apply

\[ a = \frac{(1 - \eta/k\sqrt{i})}{(1 + \eta/k\sqrt{i})}, \]
\[ b = \frac{2}{(1 + \eta/k\sqrt{i})}. \]

Since \( \eta/k \gg 1 \), the above relations become \( a \approx -1; \)
b ≈ 2√I/(γ/k). At the ground surface, z = 0, the electric and magnetic fields are respectively

\[(Ex)_{z=0} = 2\sqrt{I}/(γ/k)\]  \hspace{1cm} (25)

\[(Hy)_{z=0} = 2/c\]  \hspace{1cm} (26)

Equation (26) gives the important result that the horizontal varying field at the earth's surface is independent of both the ground conductivity and the frequency of the magnetic oscillations when these oscillations originate from a source of infinite dimensions. This implies that the constant A_1 in equation (22) is proportional to \(1/\sqrt{\delta T}\).

If the micropulsations observed on the surface of a uniform earth arise from an external source of very large dimensions then the following conclusions may be drawn:

1. The vertical component of the pulsations should be zero.

2. In a horizontal plane, the vector properties of the pulsations are determined only by the pulsation source.

2.4 Magnetic Field Variations over a Uniform Earth Due to a Localized Source.

JACOBS and SINNO (1960b) have drawn an ideal overhead current system capable of explaining some micropulsation types observed on the earth's surface. SAITO (1962) at least
believed that certain types of micropulsations have their origin in a system of ionospheric currents. JACOBS and WATANABE (1964) suggested that micropulsations in middle and low latitudes are due to ionospheric currents induced by hydromagnetic oscillations of the magnetic field lines. If the source of micropulsations lies in an ionospheric current system, it is clear that the earth is in the near field of such a radiator, because at micropulsation frequencies, the ionosphere-earth distance is only a small fraction of a wavelength. In this case the dimensions of the source are not infinite. PRICE (1962) has shown that $\psi$ for ionospheric sources ranges from $1.6 \times 10^{-9}$ for global fields to $1.6 \times 10^{-7}$ for very local fields. The case in which $\psi$ assumed the smallest value possible - $\psi = 0$ - has been discussed. In this section $\psi$ will assume the largest value appropriate to an ionospheric source - $1.6 \times 10^{-7}$. The results obtained when $\psi$ assumed intermediate values will clearly be intermediate to the results obtained in this section and in section 2.3.

For an ionospheric source, all equations derived in section 2.2 are still valid. Outside the earth $\omega_z = 0$, and on the earth's surface where $z = 0$, equation (17) becomes

$$Z(0) = \omega_n + \omega_s,$$

while above the earth's surface
Substituting the expression for \( \frac{\partial Z}{\partial z} \) in equation (18) gives

\[
iwH = -e^{iw}\left[\left(-Ce^{-\nu z} + Be^{\nu z}\right)\frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}\right]v^2P\left(Ce^{-\nu z} + Be^{\nu z}\right)
\]

(28b)
i.e. \( iwH = -\text{grad} \left(-Ce^{-\nu z} + Be^{\nu z}\right)P(x,y,\psi) \). (29)

Hence the scalar potential, \( \psi \), of the magnetic field outside the earth is

\[
\psi = \frac{(Ce^{-\nu z} + Be^{\nu z})P(x,y,\psi)}{iw}
\]

(30)

\[
= (Ae^{-\nu z} + Be^{\nu z})P(x,y,\psi)
\]

(31)

where \( A = -\frac{C}{iw} \); \( B = \frac{B}{iw} \). (32)

Since \( \psi \) is real and positive the term involving \( Ae^{-\nu z} \) increases with increasing height above the earth's surface. It therefore corresponds to a magnetic inducing field situated above the earth. For similar reasons the term involving \( Be^{\nu z} \) corresponds, in the region above the earth, to the field of the induced currents. Thus as should be expected, the magnetic field outside the earth consists of two parts: the inducing field and the induced field. It is important to note that unlike the case of an infinite source equation (28b) shows that there is a vertical component for a finite source.
To find the relation between the inducing and the induced field, it is convenient to evaluate the electric and magnetic fields inside the earth. The electric and magnetic fields are given respectively by equations (12) and (18), and $Z$ is given by equation (15). Clearly, the fields must tend to zero at very great depths. Thus from equations (12), (15) and (18) it is necessary that $Z(z) \to 0$ as $z \to +\infty$. Therefore the solution of equation (15) is

$$Z = C_0 e^{-\Theta z}$$  \hspace{1cm} (33)

Since the tangential $E$ is continuous at the earth's surface, it follows from equations (12), (17) and (33) that

$$C_0 = C + C$$  \hspace{1cm} (34)

The continuity of tangential $H$ at the surface of the earth shows, after making use of equations (17), (18) and (33), that

$$-\Theta C_0 = \nabla(-C + B).$$  \hspace{1cm} (35)

Elimination of $C_0$ between equations (34) and (35) gives

$$B = -C_0 \frac{\partial - \nabla}{\Theta + \nabla}$$  \hspace{1cm} (36)

or from equation (32)

$$B = A \frac{\partial - \nabla}{\Theta + \nabla}$$  \hspace{1cm} (37)

As was remarked earlier $A$ and $B$ are related respectively to the scalar potential of the inducing and the induced fields. Thus equation (37) gives a relation between the inducing and induced scalar potentials of the varying magnetic field.
So far the only limitation that has been imposed on the external source of the varying magnetic field is that it should have a finite dimension. The equations of this section give solution for the particular case when the potential of the source field has the form \(A e^{i\omega t} - \nabla P(x,y,z)\).

In order to obtain a quantitative estimate of the effect of ground conductivity on the vector property of the measured field corresponding to any given source field, it is necessary to have a mathematical expression for the scalar potential of the inducing field. In this case, PRICE (1950 and 1962) has shown that the general solution corresponding to any given source field can be obtained by summation of elementary solutions of the type so far considered in this section.

As an example, PRICE considered the currents induced by an oscillating line current of intensity \(I e^{i\omega t}\) flowing in the \(y\)-direction parallel to the ground surface along \(z = -h, x = 0\). The magnetic potential, \(\mathcal{M}_e\), of this line current was shown to be of the form

\[
\mathcal{M}_e = -2I e^{i\omega t} \int_{-h}^{\infty} e^{-\psi(z+h)} \sin \psi x \, \frac{d\psi}{\psi}, \quad z > -h.
\]  

(38)

Comparing equations (31) and (38) it is seen that

\[
P(x,y,z) = \sin \sqrt{\psi} x,
\]

(39)

and

\[
A = -2I e^{i\omega t} - \sqrt{\psi} h \frac{d\sqrt{\psi}}{\psi}.
\]

(40)
Thus equation (38) corresponds to summation of terms of the form $Ae^{i\omega t} - \Psi z P(x,y,z)$. The potential, $\mathcal{H}$, of the induced magnetic field is obtained from equations (31), (37) and (38) and is given by

$$\mathcal{H} = -2i e^{i\omega t} \int \frac{\partial}{\partial y} e^{i(z-h)} \sin \frac{\nu x}{\nu} \, d\nu.$$  \hspace{1cm} (41)

The inducing and induced magnetic fields can be obtained by differentiating equations (38) and (41) respectively.

A full mathematical treatment of the electromagnetic fields due to a line current flowing parallel to and above the earth's surface has also been treated by LAW and FANNIN (1961). DOSSO (1966) has used the equations developed by LAW and FANNIN to show how the amplitude and phase of the electric and magnetic fields depend on the height of the line current above the earth's surface and on the horizontal distance of the recording station from the line source for a particular conductivity distribution inside the earth. Attention was paid only to the resultant field on the earth's surface. However, the interest here is on how the vector property of the field measured on the earth's surface is related to the vector property of the inducing field, whose potential is assumed to be of the form $Ae^{i\omega t} - \Psi z P(x,y,z)$. It is also assumed that the horizontal magnetic field is directed parallel to the x-axis. The suffix "e" will be used for the
inducing field while the suffix "i" will be used for the induced field. From equations (28b) and (32) it is seen that
\[ H_x^i = -e^{i\omega t}Ae^{-\frac{\omega t}{\lambda_0}} , \quad H_x^e = -Be^{i\omega t - \frac{\omega t}{\lambda_0}} \]
\[ H_z^i = A\sqrt{\text{Pe}}e^{i\omega t - \frac{\omega t}{v}} , \quad H_z^e = -B\sqrt{\text{Pe}}e^{i\omega t - \frac{\omega t}{v}} \]
Hence from the above and equation (37) we have
\[ \frac{H_x^i}{H_x^e} = \frac{\theta - \nu}{\theta + \nu} \quad \text{(42)} \]
and
\[ \frac{H_z^i}{H_z^e} = -\frac{\theta - \nu}{\theta + \nu} \quad \text{(43)} \]
therefore
\[ \frac{H_x^i}{H_x^e} = -\frac{H_z^i}{H_z^e} = \frac{\theta - \nu}{\theta + \nu} = \kappa \quad \text{(44)} \]
Equation (44) gives the relation between the induced and inducing magnetic fields in both the horizontal and vertical planes.

Now, \[ \theta^2 = \nu^2 + 4\pi \sigma \text{iw} \quad \text{(16)} \]
therefore
\[ \frac{\theta - \nu}{\theta + \nu} = \sqrt{(4\pi \sigma \text{iw} + \nu^2)^2 - \nu^2} = \sqrt{(\nu^2 + 1)^2 - 1} \quad \text{(45)} \]
where \( \kappa = 4\pi \omega \text{w}/\nu^2 \quad \text{(46)} \)
Thus the ratio of the inducing to the induced field depends on \( \kappa \) which itself depends on both the ground conductivity and the frequency of the varying field. For instance, if
\[ \sigma = 10^{-12} \text{ e.m.u.}, \text{ and } w = 2\pi/40 \text{ (i.e., 40 secs) then } \alpha \approx 100. \]

If \( \sigma = 10^{-13} \text{ e.m.u.}, \) then \( \alpha \approx 10; \) while if \( \sigma = 10^{-14} \text{ e.m.u.}, \)

\( \alpha \approx 1.0 \) and \( \alpha < 0.1 \) for \( \sigma = 10^{-5} \text{ e.m.u.} \)

Over the earth's surface and its interior, the conductivities that may be encountered range from \( 10^{-11} \text{ e.m.u.} \), corresponding to the conductivity of sea water, to \( 10^{-16} \text{ e.m.u.} \) corresponding to the conductivity of granitic rocks. Thus the value of \( \alpha \) for micropulsations of 40 seconds period will range from about \( 10^3 \) over the oceans to \( 10^{-2} \) over very dry granitic rocks. If these values of \( \alpha \) are substituted in equation (45) it will be observed that the ratio of the induced to the inducing field varies over a wide range. Curve (A) in Fig. 2.2 shows the variation of the modulus of the ratio with \( \alpha \), while Curve (B) represents its argument. It is to be observed that for \( \alpha > 10 \) the modulus of the ratio approaches unity while the argument approaches zero. This means that the horizontal inducing and induced fields are nearly equal in magnitude and phase, while the inducing and induced vertical fields tend to cancel each other. At very large values of \( \alpha \) (\( \alpha \to 0 \)), the vertical field vanishes while the horizontal field becomes double the magnitude of the inducing field. This agrees with the conclusions arrived at in section 2.3.
FIG. 22. ILLUSTRATING THE VARIATION OF (A) MODULUS, (B) ARGUMENT OF "INDUCTION COEFFICIENT" AND (C) THE RATIO OF THE VERTICAL COMPONENT TO THE HORIZONTAL COMPONENT OF THE VARYING MAGNETIC FIELD WITH $\alpha$. $\kappa$ is defined as $\kappa = 4\pi (\omega l/\mu)^{1/2}$. $\omega$ and $\mu$ are respectively the ground conductivity and angular frequency of the oscillating current system. $\lambda l$ is a measure of the horizontal extent of the current source.
Because the recording instrument cannot discriminate between the inducing and the induced fields, it will be more appropriate to express the two fields in terms of the resultant or total field. Now the resultant field in the x-direction is

$$H_x^o + H_x^i = H_x^o (1 + \chi) = H_x.$$  \hspace{1cm} (47)

Similarly

$$H_z^o + H_z^i = H_z^o (1 - \chi) = H_z.$$ \hspace{1cm} (48)

The amplitude ratio of vertical to horizontal field is given by

$$\frac{|H_z|}{|H_x|} = \frac{|H_z^o|}{|H_x^o|} \cdot \frac{1 - \chi}{1 + \chi}.$$ \hspace{1cm} (49)

The term $H_z^o/H_x^o$ depends entirely on the source of the magnetic variation. In particular it does not depend on the ground conductivity. Since the interest here is on the effect of the ground conductivity on the ratio, $H_z/H_x$, $H_z^o/H_x^o$ may be set equal to unity without loss of generality.

Therefore

$$\frac{|H_z|}{|H_x|} = \frac{1 - \chi}{1 + \chi}.$$ \hspace{1cm} (50)

It is easy to show that

$$\frac{1 - \chi}{1 + \chi} = \sqrt{1 + \chi^2}.$$ \hspace{1cm} (51)

A graph of $1/\sqrt{1 + \chi^2}$ against $\chi$ is shown in Curve (C) of Fig. 2.2. This curve shows how the ratio of the total
vertical field to the total horizontal field varies with $\alpha$. For values of $\alpha$ greater than 10 the ratio decreases rapidly from 0.3 at $\alpha = 10$ to under 0.09 at $\alpha = 100$. However, at values of $\alpha$ less than 1, the ratio is nearly equal to one. As was remarked earlier, probable values of $\alpha$ for ionospheric current sources of about 40 seconds period range from 1000 to 0.01. In this range of $\alpha$, the ratio of the vertical component to the horizontal component of the magnetic field varies roughly between 0.03 and 1. Thus the vector property of pulsations in both vertical and horizontal planes may be much affected by ground conductivity, if the pulsations arise from ionospheric sources. Thus the vector characteristics of recorded geomagnetic variations on the earth's surface may be very different from those of the inducing external magnetic field.

If micropulsations originate from the ionosphere the following may be expected if observations are made on the earth's surface.

1. The amplitudes and phases of the variation vectors in both vertical and horizontal planes will depend on the ground conductivity.

2. Very small values of the vertical component of the pulsations do not necessarily mean that the inducing vertical component is also small.
3. The amplitudes and hence energies associated with the pulsations may vary from station to station. The magnitude of the variation will depend on the configuration of the ionospheric source and on the subsurface conductivity contrast between the stations.

2.5 The Magnetic Field Variations Due to an External Source of Infinite Size Over a Layered Earth.

In the previous sections the subsurface was assumed to be of uniform conductivity. In this section and the next, the approximate effects of layering of the earth on recorded magnetic variations are discussed. A two layered earth model is considered.

Fig. 2.3 shows a two layered earth model in which the bottom layer of uniform conductivity $\sigma_2$, starts at $z = D$ cms and extends to infinity. The top layer has a uniform conductivity $\sigma_1$ and a thickness $D$ cms. In the bottom layer, equations (20) and (22) hold, with $\sigma_2$ replacing $\sigma_1$, i.e.

$$E_z = A_1 e^{i\omega t} \left( \frac{\partial P}{\partial y} - \frac{\partial P}{\partial x} \right) \exp \left( - \sqrt{i \omega \sigma_2} z \right)$$ (52)

and

$$H = A_1 \sqrt{2\frac{\sigma_1}{\omega}} \left( \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y} \right) \exp (wt - i\omega/4 - \sqrt{i \omega \sigma_2} z)$$ (53)

In the top layer, the expression for $Z$ is given by equation (15) and therefore contains a term which increases with
FIG. 23. TWO LAYERED EARTH
increasing \( z \). Thus in the top layer solutions corresponding to equations (52) and (53) will have terms which increase with increasing \( z \). By making use of equations (12) to (18) it is easy to show that the electric and magnetic fields in the top layer are respectively given by

\[
E_1 = \left\{ A_2 \exp(\sqrt{\frac{\mu}{\varepsilon}} izz) + A_3 \exp(-\sqrt{\frac{\mu}{\varepsilon}} izz) \right\} \left\{ \frac{\partial P}{\partial y}, \frac{\partial P}{\partial x}, 0 \right\} e^{i wt} \quad (54)
\]

\[
H_1 = \sqrt{2\pi} \left\{ -A_2 \exp(\sqrt{\frac{\mu}{\varepsilon}} izz) + A_3 \exp(-\sqrt{\frac{\mu}{\varepsilon}} izz) \right\} \left\{ \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}, 0 \right\} \quad (55)
\]

The continuity of the electric and magnetic fields at the boundary \( z = D \) involves the two conditions

(a) \( A_2 e^{\sqrt{\frac{\mu}{\varepsilon}} izz} + A_3 e^{-\sqrt{\frac{\mu}{\varepsilon}} izz} = A_1 e^{-\sqrt{\frac{\mu}{\varepsilon}} izz} \quad (56) \)

(b) \( -A_2 e^{\sqrt{\frac{\mu}{\varepsilon}} izz} + A_3 e^{-\sqrt{\frac{\mu}{\varepsilon}} izz} = A_1 e^{-\sqrt{\frac{\mu}{\varepsilon}} izz} \quad (57) \)

Solving for \( A_2 \) and \( A_3 \) in terms of \( A_1 \) it is easily shown that

\[
A_2 = \frac{A_1}{2} \left( \sqrt{\frac{\mu}{\varepsilon}} - \sqrt{\frac{\mu}{\varepsilon}} \right) e^{-D/\sqrt{\mu \varepsilon} (\sqrt{\frac{\mu}{\varepsilon}} + \sqrt{\frac{\mu}{\varepsilon}})} \quad (58)
\]

\[
A_3 = \frac{A_1}{2} \left( \sqrt{\frac{\mu}{\varepsilon}} + \sqrt{\frac{\mu}{\varepsilon}} \right) e^{D/\sqrt{\mu \varepsilon} (\sqrt{\frac{\mu}{\varepsilon}} - \sqrt{\frac{\mu}{\varepsilon}})} \quad (59)
\]

Thus the surface magnetic field, \( H \), is given by

\[
H = A_1 \sqrt{\frac{\mu}{\varepsilon}} \left\{ \left( \sqrt{\frac{\mu}{\varepsilon}} + \sqrt{\frac{\mu}{\varepsilon}} \right) e^{D/\sqrt{\mu \varepsilon} (\sqrt{\frac{\mu}{\varepsilon}} - \sqrt{\frac{\mu}{\varepsilon}})} - \left( \sqrt{\frac{\mu}{\varepsilon}} - \sqrt{\frac{\mu}{\varepsilon}} \right) e^{-D/\sqrt{\mu \varepsilon} (\sqrt{\frac{\mu}{\varepsilon}} + \sqrt{\frac{\mu}{\varepsilon}})} \right\} \left\{ \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}, 0 \right\} \quad (60)
\]

Now if the magnetic field is assumed to be directed along the \( x \)-axis then equation (60) becomes
where \( B = A_1 \sqrt{T/2} \cdot \frac{\partial \mathcal{P}}{\partial x} \). \( (62) \)

As a check on the consistency of equation (61), putting \( \sigma_1 = \sigma_2 = \sigma \), then since for an infinite source \( \partial \mathcal{P}/\partial x \) is constant the surface magnetic field becomes

\[
H_x = B \ 2\sqrt{\sigma} = A_1 \sqrt{2\sigma T}. \quad (63)
\]

This is the same as equation (22) of section 2.3 where it was observed that \( A_1 \) is proportional to \( 1/\sqrt{\sigma T} \), thus making the surface magnetic field independent of the ground conductivity when the latter is homogeneous. This suggests that the constant \( B \) in equation (61) is a function of \( \sigma_1, \sigma_2, T \) and \( D \). That \( B \) is proportional to the reciprocal of the expression within the square brackets in equation (61) may be verified as follows: since from equation (54) the vertical component of the electric field and hence the vertical component of the current density, \( i_z \), is zero, it follows from equation (1) that

\[
-\frac{\partial H_x}{\partial y} = 4\pi i_z = 0, \quad (64)
\]

where \( H_x \) is the surface magnetic field. This means that the surface magnetic field is constant on the earth's surface. Since the surface magnetic field is given by equation (61) if follows that \( B \) in that equation is proportional to the
reciprocal of the expression in the square bracket. This is consistent with the surface magnetic field, \( H_x \), being independent of the conductivity distribution inside the earth. Thus layering of the subsurface is not expected to affect the horizontal components of the micropulsation fields if these originate from a source of indefinite dimensions.

Though only a particular model of the subsurface has been considered here, a more rigorous mathematical treatment by DOSSO (1962, 1965) shows that the value of the horizontal component of the magnetic field is not affected by the layering of the subsurface. However, DOSSO found that both the phase and amplitude of the vertical component (if present) at the surface are strongly dependent on the structure of the subsurface.

2.6 The Magnetic Field Variation Due to an External Source of Finite Dimensions Over a Layered Earth.

As in the last section the subsurface is considered to consist of two layers as shown in Fig. 2.3; the top layer of conductivity \( \sigma_1 \) has a thickness \( D \) cms; the bottom layer starts at a depth \( D \) cms and extends to infinity. Its conductivity is \( \sigma_2 \). The aim here is to estimate the effect of layering of the subsurface on the recorded magnetic field, whose origin lies above the earth. The equations developed
in section 2.2 giving the electric and magnetic fields in and above the ground, which will be needed in this section, are quoted below.

\[ \bar{E} = e^{i\omega t} Z(z) \left( \frac{x}{\partial y}, -\frac{y}{\partial x}, 0 \right), \]  \hspace{1cm} (12) \\
\[ i\omega \bar{H} = -e^{i\omega t} \left\{ \frac{\partial Z}{\partial x}, \frac{\partial Z}{\partial y}, \nabla^2 PZ \right\} \]  \hspace{1cm} (18) \\

where outside the ground

\[ Z = \alpha e^{-\gamma z} + \beta e^{\gamma z} \]  \hspace{1cm} (17)

and

\[ \left( \frac{\partial Z}{\partial z} \right)_{z=0} = -\alpha \gamma + \beta \gamma \]  \hspace{1cm} (65)

Inside the earth

\[ Z = \gamma e^{\theta z} + \beta e^{\theta z} \]  \hspace{1cm} (15)

where

\[ \theta = \gamma^2 + n \sigma \omega \]  \hspace{1cm} (16)

and

\[ \left( \frac{\partial Z}{\partial z} \right)_z = -\alpha \theta e^{\theta z} + \beta \theta e^{\theta z} \]  \hspace{1cm} (66)

The expressions for the electric and magnetic fields in the different layers will be different because Z is not the same in any two layers. Continuity of the horizontal fields at the boundary between two layers implies that Z must have to be continuous if the electric fields are considered, (c.f. equation (12) above), or the derivative of Z with respect to z, if the tangential magnetic field is considered. Clearly Z in the bottom layer must have the coefficient in the second term on the right hand side of the equation (15) equal to
zero if infinite values of $Z$ and hence electric fields are not to be admitted. Thus in this layer

$$Z = \zeta_2 \varepsilon_2 \varepsilon_0$$  \hspace{1cm} (67)

The subscript "s" will be used to denote quantities in the free space above the earth; "1" will be used to subscript quantities in the top layer and "2" will be used to subscript quantities in the bottom layer.

The continuity of the tangential electric field at the ground surface requires, (from equations (12), (17) and (15))

$$\zeta_s + \zeta_1 = \zeta_1 + \zeta_2$$  \hspace{1cm} (68)

The continuity of the tangential electric field at depth $D$ implies that

$$\zeta_2 \varepsilon_2 \varepsilon_0 = \zeta_1 \varepsilon_1 \varepsilon_0 + \zeta_1 \varepsilon_1 \varepsilon_0$$  \hspace{1cm} (69)

The continuity of the tangential magnetic field at $z=0$ and $z=D$ gives respectively

$$\zeta_s \psi_1 - \zeta_s \psi_0 = \Theta_1 (\zeta_1 \psi_0 - \zeta_1 \psi_1)$$  \hspace{1cm} (70)

and

$$\Theta_2 \zeta_2 \varepsilon_2 \varepsilon_0 = \Theta_1 (\zeta_1 \varepsilon_1 \varepsilon_0 - \zeta_1 \varepsilon_1 \varepsilon_0)$$  \hspace{1cm} (71)

If these equations are solved for $\zeta_s$ and $\zeta_2$, it will be found that

$$\frac{\partial \psi}{\partial z} = \frac{1}{(\Theta_1 + \psi)} \left( \frac{1}{\Theta_1 + \psi} \right) \frac{\varepsilon_2^2 \psi_0}{\varepsilon_1^2 \psi_1}$$ \hspace{1cm} (72)

If the scalar potentials of the inducing and induced field are respectively in the form $A_s e^{i \omega t - v z}$ and $B_s e^{i \omega t + v z}$, then from
equation (32) it is seen that
\[ A_s = -\frac{B_s}{1w}; \quad B_s = \frac{B_s}{1w}. \] (73)
Hence
\[ \frac{(\mathcal{A}_s)}{\mathcal{B}_s} = \frac{B_s}{A_s}. \]
Therefore (72) becomes
\[ B_s = A \frac{(\mathcal{G}_1 - \mathcal{V}) - (\mathcal{G}_1 + \mathcal{V}) \left( \frac{\mathcal{G}_1 - \mathcal{G}_2}{\mathcal{G}_1 + \mathcal{G}_2} \right) \xi^2 \varepsilon_1 \varepsilon_2}{(\mathcal{G}_1 + \mathcal{V}) - (\mathcal{G}_1 - \mathcal{V}) \left( \frac{\mathcal{G}_1 - \mathcal{G}_2}{\mathcal{G}_1 + \mathcal{G}_2} \right) \xi^2 \varepsilon_1 \varepsilon_2}. \] (74)
The above equation gives the relation between the inducing and induced scalar potentials of the varying magnetic field. As in section 2.41, the above equation may be shown to give the relation between the inducing and induced magnetic fields when the latter is in the form \( A_0 e^{i\omega t - \mathcal{V}z} \). A check on the consistency of equation (74) is made by putting \( \mathcal{G}_1 = \mathcal{G}_2 \). This gives immediately equation (37).

An idea of how the induced field changes with \( \mathcal{G}_1 \) and \( \mathcal{G}_2 \) may be obtained by substituting different values of \( \mathcal{G}_1 \) and \( \mathcal{G}_2 \). For country rocks, \( (\varepsilon = 10^{-12} \text{ e.m.u.} \text{ to } 10^{-15} \text{ e.m.u.}) \) values of \( \varepsilon \) are likely to be in the range \( 10^{-6} \) to \( 10^{-7} \). Thus for depths of less than one kilometre, \( \mathcal{G}_1^D < 1 \). At such depths it may be permissible, as a first approximation, to put \( e^{-2\mathcal{G}_1^D} \approx 1 \). If this is done equation (74) becomes
\[ \frac{B_s}{A_s} \approx \frac{\mathcal{G}_1 \varepsilon_2}{\mathcal{G}_1 \varepsilon_2}, \]
while for large values of \( \mathcal{G}_1^D \) or small values of \( \varepsilon_1 - \varepsilon_2 \)
equation (74) becomes

$$\frac{B}{A} = \frac{\theta - \sqrt{\theta}}{\theta + \sqrt{\theta}}$$

Obviously for intermediate values of $\theta_1 D$, $B/A$ lies between $(\theta_1 - \sqrt{\theta_1} + \sqrt{\theta})$ and $\frac{\theta_2 - \sqrt{\theta_2} + \sqrt{\theta}}{\theta + \sqrt{\theta}}$. Thus the value of

$$\frac{B}{A} = \frac{\theta - \sqrt{\theta}}{\theta + \sqrt{\theta}} \quad (75)$$

where $\theta$ is intermediate between $\theta_1$ and $\theta_2$ and may be related to the mean conductivity down to the skin depth of the particular variation.

The above discussion has been for a two layered subsurface, but the arguments can be extended to any number of layers. Now, since the induced currents flow parallel to the surface the resistances of the layers are in parallel. If there are $n$ layers within the depth $z$ and the conductivity of the layers are given by $f_1(z), f_2(z), \ldots, f_n(z)$ and if the interfaces are at depths $h_1, h_2, \ldots, h_{n-1}$, then the mean conductivity $\overline{\sigma}$ of the layers is given by

$$\overline{\sigma} = \frac{1}{z} \left\{ \int_{h_1}^{h_2} f_1(z) \, dz + \int_{h_2}^{h_3} f_2(z) \, dz + \cdots + \int_{h_{n-1}}^{z} f_n(z) \, dz \right\}.$$  

On the other hand, if the conductivity varies continuously with depth then the mean conductivity to a depth $z$ is

$$\overline{\sigma} = \frac{1}{z} \int_{0}^{z} f(z) \, dz.$$  

Thus no matter how conductivity varies with depth, its mean down to the skin depth may be used to find the value of $B/A$ in equation (75). Now equation (75) is exactly the same as that for a homogeneous earth whose parameter ($\gamma^2 + 4 \mu_i \omega$) is $\theta^2$. 


(equation (37)). Thus as with a homogeneous subsurface, magnetic variations due to ionospheric source, observed over a subsurface where the conductivity varies with depth may be expected to exhibit characteristic differences between observing stations. The differences will be controlled by the mean conductivity (as seen by the magnetic variations) and the dimensions of the source in the manner shown in Fig. 2.2.

In conclusion it may be said that there is no difference in the amplitudes of magnetic variations measured over a homogeneous ground and over a subsurface with variable conductivity, if the mean conductivity down to the skin depth of the variations, in the latter is equal to the conductivity of the homogeneous ground.

2.7 The Effect of Lateral Conductivity Variations on Recorded Pulsations.

So far, the subsurface has been assumed to be horizontally homogeneous. A number of geophysicists including d'ERCEVILLE and KUNETZ (1962) interested in the use of the magnetotelluric method for geophysical exploration have studied the effect of subsurface lateral conductivity discontinuity on the electromagnetic field. A report of peculiar behaviour of geomagnetic micropulsations at a Canadian coastal station
prompted WEAVER (1963) to examine the effect of a land-sea boundary on short period geomagnetic variations. Because

WEAVER's theory is discussed in some detail here. However, details of mathematical derivation are omitted; only a general approach is given.

The subsurface is assumed to be divided into two regions of different conductivity by a vertical plane. Within each region the electrical properties of the ground are isotropic and homogeneous. The boundary separating the two regions is chosen as the x-axis of a rectangular coordinate system. The surface of the ground is represented by the plane z=0, with the z-axis directed downwards into the ground. The plane y=0 divides the half space, z>0, into two regions of conductivity \( \sigma_1 \) and \( \sigma_2 \). Fig. 2.4 shows the coordinate system in relation to the two regions, the boundary of the two regions is the vertical plane passing through 0. It is assumed that \( \sigma_2 \gg \sigma_1 \). As previously \( \textbf{E} \) stands for the electric field vector and \( \textbf{H} \) for the magnetic field vector. To indicate to which region a quantity belongs the subscripts 1 and 2 are used. Electric and magnetic fields are assumed to depend on time through the factor \( e^{i\omega t} \).

Within each region the electromagnetic fields satisfy Maxwell's equations. Equations similar to equation (6) can be written for each of the field quantities i.e.,

\[ \nabla \cdot \textbf{E}^2 = 4\pi \mu_0 \text{im} \textbf{E} = i\gamma \textbf{E} \]  

(76)
FIG. 2.4. PLANE CONDUCTING EARTH WITH COASTAL BOUNDARY
and
\[ \nabla^2 \mathbf{H} = \frac{4\pi i}{c} \mathbf{w} \mathbf{H} = i \gamma^2 \mathbf{H} \quad (77) \]

where \( \gamma^2 = \frac{4\pi i}{c} \mathbf{w} \).

It is assumed that the electromagnetic wave is plane polarized such that either the magnetic vector (H polarization) or the electric vector (E polarization) is parallel to the \( x \)-axis. With this assumption the curl equations (1) and (2) become, after neglecting displacement currents,

\[ E_x = 0, \quad E_y = \frac{\omega}{c} \frac{\partial H_z}{\partial z}, \quad E_z = -\frac{\omega}{c} \frac{\partial H_y}{\partial y} \quad (78) \]

\((H\text{ polarization})\)

\[ H_x = 0, \quad H_y = \frac{i}{c} \frac{\partial E_x}{\partial z}, \quad H_z = -\frac{i}{c} \frac{\partial E_y}{\partial y} \quad (79) \]

\((E\text{ polarization})\)

For \( H \) polarization, equation (77) becomes

\[ \frac{\partial^2 H_x}{\partial y^2} + \frac{\partial^2 H_z}{\partial z^2} = i \gamma^2 H_x \quad (80) \]

while for \( E \) polarization (76) gives

\[ \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} = i \gamma^2 E_x \quad (81) \]

In section 2.3 it was shown that in the case of plane waves, the electric and magnetic fields are given respectively by

\[ (E_x)_{z=0} = 2 \sqrt{i/(i/k)} , \quad (25) \]

and

\[ (H_y)_{z=0} = 2/c , \quad (26) \]
where \( c \) is the velocity of light and \( k = \omega/c \). Equation (26) gives the important result that the amplitude of the horizontal magnetic field is independent of the ground conductivity at micropulsation frequencies and for conductivity generally the smaller the dimensions of the source the greater is the effect of likely to be encountered inside the earth. Thus, even abrupt changes in the conductivity of the ground on the horizontal magnetic field. It is therefore a constant. This fact gives one of the boundary conditions to be used later. It is to be observed from equation (25) that the surface electric field depends on the conductivity of the ground and will therefore vary across the discontinuity. It is this variation which, by the relations expressed in equation (79), introduces a vertical component of the magnetic field whose magnitude depends on the conductivity contrast at the discontinuity. It is important to note here that the vertical component of the magnetic field arises only in the case of E polarization, as is clear from equations (78) and (79). Thus if the vertical field arises entirely from the conductivity contrast at the boundary, its magnitude will depend, among other things, on the direction of polarization of the horizontal magnetic field relative to the discontinuity boundary. Since it is only in the case of E polarization that there is a perturbation of the magnetic field, only this case is discussed here. The subscript 'x'
is omitted from $E_x$ since with $E$ polarization this is the only electric field entering the problem. The electric fields in regions 1 and 2 are denoted by $E_1$ and $E_2$ respectively, while the magnetic fields are $H_1$ and $H_2$ respectively.

The boundary conditions required for the solution of equation (81) are enumerated below:

(i) $\frac{\partial E_1}{\partial z} = \frac{\partial E_2}{\partial z} = -Bw_1$ on $z=0$ i.e. $H_y$ is constant and equal to $B$.

(ii) $E_1 = E_2 = g(z)$, say, on $y=0$ i.e. continuity of tangential $E$ at boundary.

(iii) $\frac{\partial E_1}{\partial y} = \frac{\partial E_2}{\partial y}$ on $y=0$ i.e. $H_z$ is continuous at $y=0$.

(iv) $E_1, E_2, \frac{\partial E_1}{\partial z}, \frac{\partial E_2}{\partial z} \rightarrow 0$ as $z \rightarrow \infty$.

(v) $E_1 = 0$ as $y \rightarrow -\infty$, $E_2 = 0$ as $y \rightarrow +\infty$.

The Fourier integral transform method of solution of differential equations is used. The Fourier cosine transform, $\hat{\Phi}(\bar{\omega})$, of a function $\Phi(z)$ is defined as

$$\hat{\Phi}(\bar{\omega}) = \sqrt{2\pi} \int_{-\infty}^{\infty} \Phi(z) \cos \bar{\omega} z \, dz$$

while the inverse transform is defined as

$$\Phi(z) = \sqrt{2\pi} \int_{-\infty}^{\infty} \hat{\Phi}(\bar{\omega}) \cos \bar{\omega} z \, d\bar{\omega}.$$ 

The solution of equation (81) proceeds by taking its Fourier cosine transform and integrating with the aid of (i) and (iv), when it will be found that
\[
\frac{\partial \bar{E}}{\partial t} = j - i \bar{B} \times \bar{i} \tag{82a}
\]

where, as explained above, \( \bar{E} \) is the transform of \( E \) and
\[
\mu^2 = \beta^2 + i \eta^2 \tag{82b}
\]

On integrating equation (82a) and making use of (ii) and (v) it is found that
\[
E_1 = \frac{B\omega I}{\eta_1} e^{-z_1 I} + \frac{2}{\eta_1} \int_0^\infty \left( \sqrt{\eta_2} \bar{J}(z) - \frac{B\omega i}{\beta I} \right) e^u_1 \cos \beta Z d\beta (83)
\]
and
\[
E_2 = \frac{B\omega I}{\eta_2} e^{-z_2 I} + \frac{2}{\eta_2} \int_0^\infty \left( \sqrt{\eta_2} \bar{J}(z) - \frac{B\omega i}{\beta I} \right) e^u_2 \cos \beta Z d\beta (84)
\]

By use of the boundary condition (iii) it is found that
\[
\bar{J}(z) = \sqrt{\eta_1} \frac{B\omega i}{\beta I} .
\]

The final solutions for \( E_1 \) and \( E_2 \) are therefore
\[
E_1 = \left( \frac{B\omega I}{\eta_1} \right) e^{-z_1 I} + \left( \frac{2B\omega i}{\eta_1} \right) \frac{u_1}{u_1 - u_1} e^u_1 \cos \beta Z d\beta \]
\[
E_2 = \left( \frac{B\omega I}{\eta_2} \right) e^{-z_2 I} + \left( \frac{2B\omega i}{\eta_2} \right) \frac{u_2}{u_2 - u_2} e^u_2 \cos \beta Z d\beta
\]

From the above equations and equation (79) the corresponding magnetic fields are found to be
\[
(\bar{H}_1)_y = \bar{B} \bar{J} e^{-z_1 I} + \frac{2B\omega i}{\eta_1} \int_0^\infty \frac{u_1}{u_1 - u_1} e^u_1 \cos \beta Z d\beta
\]
\[(H_2)_y = \frac{2 \pi \gamma_2}{n} \int_0^\infty \left( \frac{\gamma_2 - \gamma_1}{\gamma_2} \right) e^{i \omega \gamma_1} \cos \gamma_2 \gamma_1 \, d\gamma_1 \]
and
\[(H_1)_z = \frac{2 \pi \gamma_1}{n} \int_0^\infty \left( \frac{\gamma_1}{\gamma_2} \right) e^{i \omega \gamma_1} \cos \gamma_1 \gamma_2 \, d\gamma_1 .
\]

On the surface of the ground, \( z = 0 \), the ratio of the vertical to the horizontal component of the magnetic field \((Z/H)\) in each region is easily found from the above equations to be
\[
\frac{Z_1}{(H_1)_y} = \frac{2 \pi \gamma_1}{n} \int_0^\infty \left( \frac{\gamma_1}{\gamma_2 - \gamma_1} \right) e^{i \omega \gamma_1} \cos \gamma_1 \gamma_2 \, d\gamma_1 , \quad (85)
\]
\[
\frac{Z_2}{(H_2)_y} = \frac{2 \gamma_2}{n} \int_0^\infty \left( \frac{\gamma_1}{\gamma_2} \right) e^{i \omega \gamma_1} \cos \gamma_2 \gamma_1 \, d\gamma_1 . \quad (86)
\]

For computing these ratios for different values of \( w \) and \( y \), it is convenient to rearrange the above expressions by writing \( \mu = \alpha + i\beta \) and the transformation \( \gamma_2 = \eta \gamma_1 \). Use of these and equation (82b) gives
\[
\alpha_1 + i\beta_1 = \left( \gamma_2 \gamma_1 \right) \left[ \frac{1}{2} \left( \gamma_1^2 + \gamma_2^2 \right) + i \gamma_1 \left( \gamma_1 \gamma_2 \right) \right],
\]
\[
\alpha_2 + i\beta_2 = \left( \gamma_2 \gamma_1 \right) \left[ \frac{1}{2} \left( \gamma_1^2 + \gamma_2^2 \right) + i \gamma_1 \left( \gamma_1 \gamma_2 \right) \right],
\]
where \( \gamma = \sigma_1 / \sigma_2 \).
By putting
\[ p = \alpha_n \left( (u + \epsilon^1) \right)^{-\frac{4}{3}} - \alpha_n \left( (u + \epsilon^4) \right)^{-\frac{4}{3}} \]
and
\[ q = \beta_n \left( (u + \epsilon^1) \right)^{-\frac{4}{3}} - \beta_n \left( (u + \epsilon^4) \right)^{-\frac{4}{3}} \]
equations (85) and (86) can be expressed respectively as
\[ \frac{Z_1}{(\eta_1)_y} = \frac{2}{\pi} \int_0^{\infty} (\epsilon + i \eta) \ v \ \left\{ - \chi_{ij} + i \beta \ y \right\} \ d\eta, \quad (87) \]
and
\[ \frac{Z_2}{(\eta_2)_y} = \frac{2}{\pi} \int_0^{\infty} (\epsilon + i \eta) \ v \ \left\{ - \chi_{ij} + i \beta \ y \right\} \ d\eta. \quad (88) \]

WEAVER evaluated the integrals in equations (87) and (88) numerically for frequencies \( w = 1 \text{ c/s and } 1/10 \text{ c/s,} \)
and with \( C_1 = 10^{-14} \text{ e.m.u. (land) and } C_2 = 4 \times 10^{-11} \text{ e.m.u. (sea).} \)
Calculations were made for a series of values of \( y \) corresponding to different distances from the coastal boundary. The behaviour of \( \left| \frac{Z_1}{(\eta_1)_y} \right| \) and \( \frac{Z_2}{(\eta_2)_y} \) across the boundary was shown graphically.

Now, at Hartland (Devon) the dominant pulsation has a period between 30 and 40 seconds. The graphs illustrating the variation of the amplitude ratio of the vertical to horizontal component, \( \left| \frac{Z_1}{(\eta_1)_y} \right| \), of the pulsations with distance from the coast on the land side of the boundary for events with periods of 30 seconds and 40 seconds are shown in Fig. 2.5.
Fig. 2.5. Illustrating the variation of vertical magnetic component with distance from the sea coast on the land side
(A) for pulsation of 30 secs. period
(B) for pulsation of 40 secs. period
The data for these curves were extrapolated from the curve due to WEAVER. This is easily done as follows: The angular frequency $w$ only enters equations (87) and (88) in the argument of the exponential, since the factor $1/\gamma_2$ outside the integral cancels the $\gamma_2$ contained in $P$ and $q$.

Since $\gamma_2 = \sqrt{4\pi \sigma_2 w}$, the exponential term in equation (87) may be re-written as follows

$$\exp (-K_1 \gamma_2 t) = \exp (S \sqrt{w})$$

where $S$ is a complex term, independent of $w$. Thus the value of the integral is fixed for constant $y \sqrt{w} = y / \sqrt{T}$; where $T$ is the period of the variation. This means that the field at a distance $y$ for any value of $T$ has the same value as the one second field at a distance of $y / \sqrt{T}$.

Fig. 2.5 suggests that the amplitude of the vertical field component increases as the boundary is approached; the maximum value occurs at the boundary. The vertical to horizontal amplitude ratio is frequency dependent:

It is apparent that because of the obvious limitations of the model for the conductivity discontinuity boundary, only a qualitative comparison can be made between observation and theory. However, if micropulsation observations are made at stations
near and far from a conductivity discontinuity boundary such as the sea coast, if conditions are right, the following should be observed:

1. The ratio of the vertical component to the horizontal component, \( \frac{Z_i}{H_i} \), of the pulsations diminishes away from the coast.

2. The amount of the vertical field depends on the direction of polarization of the horizontal component of the pulsations relative to the sea-coast. Specifically for pulsations polarized in a vertical plane parallel to the sea coast, the vertical component is zero.

3. The amplitude ratio of the vertical to the horizontal component is frequency dependent.

2.8 Conclusion

As was reviewed in the first chapter, one belief is that micropulsations arise as a direct result of the fluctuating pressure of the solar plasma on the magnetospheric boundary. This is referred to here as the "magnetohydrodynamic theory." If in the electromagnetic approach the magnetic variations due to this could be represented by an equivalent current system at the magnetospheric boundary, one would expect the electromagnetic
waves to be plane polarized on the earth's surface. In this case the following conclusions may be drawn:-

1. The vertical component of the pulsations must be vanishingly small compared with the horizontal component at all places far from any lateral conductivity discontinuity.

2. Irrespective of the distribution of conductivity in the subsurface, the horizontal components of the pulsations are invariant on the earth's surface. However, around places of large conductivity gradient there will be an appreciable vertical component. Its magnitude will be expected (a) to depend on the direction of polarization of the horizontal component of the pulsation, (b) to be frequency dependent and (c) to decrease with increasing distance from the boundary separating the two regions of different conductivities.

The "ionospheric current theory" claims that the micropulsations arise from ionospheric currents. In this case the sources are finite and from the discussion in this chapter the following may be expected:-

1. The amplitudes and phases of the micropulsation vectors in both vertical and horizontal planes may depend on the conductivity of the subsurface.
2. The vertical component of pulsations will be present though its amplitude may be very much controlled by the ground conductivity.

3. The amplitudes and hence the energy associated with the pulsations may be expected to vary from location to location depending on the mean conductivity of the subsurface down to the skin depth of the pulsations and of course on the configuration of the ionospheric current system. As in the case of the plane wave theory, any lateral variation in the ground conductivity will affect the recorded pulsations.

From the above, it may be possible to estimate the effect of geology on recorded pulsations from the study of the vector property of pulsations for different geological environments. This may also indicate whether these pulsations are due to plane waves or localized sources.

As some of the necessary conditions in the non-conducting medium above the earth's surface do not appear to have been satisfied, it seems therefore that Weaver's treatment is not quite correct.
CHAPTER 3

THE ANALYSIS OF MICROPULSATION DATA
FROM THREE BRITISH OBSERVATORIES
3.1 Introduction

It was pointed out in the last chapter that because of geological differences, geomagnetic micropulsations recorded at different sites may exhibit structural differences. In particular, where a sharp lateral conductivity gradient exists, it gives rise to an increased vertical field component whose magnitude depends on the conductivity gradient as well as on the distance of the recording site from the discontinuity. In their investigation of micropulsation activity at middle latitudes, STUART and USHER (1966) observed, among other things, micropulsation energy differences between three British observatories. They used the total field rubidium magnetometer which responds only to pulsations with components in the direction of the total magnetic field. Any pulsation occurring in a plane perpendicular to the total field is undetected (c.f. chapter 6). It is not known to what extent this inability of the total field rubidium magnetometer to respond to pulsations polarized in a plane perpendicular to the meridian affected the conclusions.

To examine whether some of the observed differences between the stations arise as a result of differences in the component structure of the pulsations at these places, the observatory rapid run records at each station were analyzed.
Each of the observatories was visited during the second half of 1965 to collect the data for this study. Characteristic differences between pulsations at the observatories may be either an intrinsic property of the phenomenon or may be due to geological differences between the stations or a combination of these.

The observatories are at Hartland, Devon, (geomagnetic latitude $54.6^\circ N$); Eskdalemuir, Dumfrieshire, ($58.4^\circ N$) and Lerwick, Shetland ($62.5^\circ N$). Hartland Observatory is about two miles from the western sea coast. The underlying geological formation is mainly carboniferous limestone and sandstone. Eskdalemuir lies midway between the East and West coasts of southern Scotland and is about 50 miles from the sea. However, despite the presence of the Solway Firth within 30 miles of the observatory on the South it is regarded for these purposes as being relatively inland. The subsurface geology is mainly grit. Lerwick Observatory is less than half a mile from the eastern sea coast of the main Shetland Island which is less than ten miles wide near the observatory. The subsurface geology is composed of metamorphosed limestone and grit. Thus there are significant geological and environmental differences between the three observatories. The positions of these observatories are shown in Fig. 3.1
FIG. 3.1. MAP OF UNITED KINGDOM SHOWING THE POSITION OF THE THREE OBSERVATORIES
3.2 The Quality and Analysis of Observatory Records.

Obviously observatory rapid run records are not ideal for a detailed study of micropulsation vector structure. However, because of the large amount of data available, they are useful in that they give a statistical picture of the phenomenon.

The general practice, in geomagnetic work, is to denote the horizontal component of the magnetic field by $H$ and its azimuth, reckoned positive from the geographical north towards the East from $0^\circ$ to $360^\circ$, by $D$. $X$ is used to denote the component along the horizontal direction in the geographical meridian, and is reckoned positive if northward and negative if southward; $Y$ denotes the horizontal component transverse to the geographical meridian, and is reckoned positive if eastward, and negative if westward; $Z$ is the vertical component, reckoned positive if downward, and negative if upward; the total magnetic force is denoted by $F$. In this notation the components are connected by the following relations

$$X = H \cos D, \quad Y = H \sin D,$$
$$X^2 + Y^2 = H^2, \quad F^2 = X^2 + Y^2 + Z^2 = H^2 + Z^2 \quad (1)$$

If $F$ changes by a small amount $\Delta F$ and if this is small compared with the mean value of $F$, then it can be shown that
\[ \Delta X = H \cos D - \Delta H \sin D \]
\[ \Delta Y = \Delta H \sin D + \Delta D \cos D \]  
\( (2) \)

For small field changes, \( \Delta H \) and \( H \Delta D \) are horizontal rectangular field components measured in the direction of \( H \) and perpendicular to it. In other words they correspond to the magnetic north and magnetic east components respectively. In this study, horizontal rectangular field components measured in the direction of magnetic north and magnetic east will be denoted by \( X' \) and \( Y' \) respectively, while measurements made in the direction of the geographical north and east will be denoted by \( X \) and \( Y \) respectively. The relation between \( \Delta X', \Delta Y' \) and \( \Delta H, \Delta D \) is given by

\[ \Delta X' = \Delta H, \quad \Delta Y' = H \Delta D. \]  
\( (3) \)

The scale values at the observatories were as shown below in Table 3.1.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Chart</th>
<th>( X' ) in</th>
<th>( Y' ) in</th>
<th>( Z ) in</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed</td>
<td>gammas/</td>
<td>gammas/</td>
<td>gammas/</td>
<td></td>
</tr>
<tr>
<td>Hartland</td>
<td>mm/min</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>4.0</td>
<td>6.0</td>
<td>4.4</td>
<td>till 20.9.65</td>
</tr>
<tr>
<td>Eskdalemuir</td>
<td>3.0</td>
<td>5.6</td>
<td>5.3</td>
<td>4.1</td>
<td>after 20.9.65</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>1.7</td>
<td>5.3</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>6.7</td>
<td>4.1</td>
<td>4.9</td>
<td>till 1.7.58</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>7.3</td>
<td>4.1</td>
<td>4.9</td>
<td>2.7.58-12.58</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>7.3</td>
<td>4.1</td>
<td>5.2</td>
<td>1.12.58-28.2.60</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>7.15</td>
<td>4.1</td>
<td>10.45</td>
<td>1.3.61-12.12.62</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>2.5</td>
<td>4.1</td>
<td>9.36</td>
<td>13.12.62-27.10.64</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>2.5</td>
<td>4.1</td>
<td>8.0</td>
<td>after 27.10.64</td>
</tr>
</tbody>
</table>

Table 3.1 1 gamma = \( 10^{-5} \) gauss.
In terms of scale values and thickness of the traces, Hartland and Eskdalemuir records were of much better quality than those of Lerwick.

The records were scaled by hand. Because of the small scale values only events of comparatively large amplitude were scaled. At Hartland and Eskdalemuir, amplitude scaling was limited to events with a peak-to-peak amplitude of at least 0.6 mm in one of the components. In practice this meant that an event had to have a peak-to-peak amplitude of at least 2.4 gammas in X' if it was to be scaled. The errors involved in the scaling of X' and Z components did not exceed 0.25 mm, but the reading errors in Y' could be much greater than 0.3 mm. The difference in the reading errors arose from the fact that the Y' trace was often as thick as 0.3 mm.

In the scaling of the Lerwick records reading errors could be much greater than 0.3 mm in all components particularly in Y' and Z traces owing to their greater width. As a result of this, combined with the small scale values, Lerwick data is much more unreliable than those of Hartland and Eskdalemuir. Here an event qualified for scaling if its peak-to-peak amplitude exceeded 0.4 mm in any one of the components. Because of the doubts cast on the reliability of the Lerwick data, three months fluxgate records of micropulsation activity at Lerwick were also analyzed to supplement the data from observatory rapid run records.
When it is remembered that the average amplitude of micropulsations is only a few tenths of a gamma, the criterion chosen here for scaled events meant that only the largest pulsations were analyzed. It is probable that any conclusion drawn from this data may apply only to special types of micropulsations. To draw statistical conclusions from this group of pulsations required the analysis of many years records. At each observatory, good events in all records from January 1958 till September 1965 were scaled. Because of the small amplitudes often involved, events which occurred during very disturbed periods such that it was difficult to scale the peak-to-peak amplitude without incurring much error, were left out. The majority of the events scaled at Lerwick were of the pt type. However, at Hartland and Eskdalemuir, pc events were predominant. A pulsation could persist for several minutes or even for hours during which its amplitude often changed. The amplitude associated with an event was the maximum amplitude developed and the time of occurrence of this maximum amplitude was taken as the time of occurrence of the event. The periods of events, defined as the average time separating two adjacent peaks in a train of pulsations, were noted and these were reckoned to be correct within five seconds. No attempt was made to distinguish the sense of the vectors or to note their phase relationship. To help in the identification of
possibly simultaneous events at the three observatories, the date and time of occurrence of the maximum amplitude were noted. Using the scale values the millimetre readings were converted to gammas.

3.3 The Treatment of the Data.

The main interest in this analysis was in the distribution of amplitudes among the micropulsation components. The discussions on the possible effect of the site on the recorded geomagnetic micropulsations (chapter 2) indicated that the ground conductivity affected the structure of pulsations in the horizontal plane as recorded on the earth's surface less than those in the vertical plane. In a horizontal plane, therefore, characteristic vector property of the recorded pulsation is expected to be very similar to that of the external source field in that same plane. Thus the distribution of amplitudes between the horizontal components may give information regarding the polarization of the external micropulsation source field. However, in a vertical plane the structure of the recorded pulsations may be very much different from that of the external source field. Irrespective of the origin of micropulsations, it is reasonable to expect that there exists some correlation between the pulsation components which may be related to the mode of
propagation of the disturbances, to the propagation path, to the influence of the recording site or to any combination of these. In searching for this correlation, the amplitude ratios between two mutually perpendicular components were evaluated and their variation with period and time of day were examined. In particular, for each scaled event at each station the ratio of the magnetic E-W component to the N-S component \( \frac{Y'}{X'} \) was evaluated. Graphs of this ratio against local time and period were plotted.

In any vertical plane, a correlation between the vertical and the horizontal components of pulsations confined in that plane was sought for. This method of analysis was dictated by the theory due to Weaver (1963), and discussed in Chapter 2, which expects increased vertical components at coastal stations. At such stations the relationship between the vertical and horizontal amplitude ratios is expected to exhibit a directional property. It seems reasonable to expect that any relationship between the vertical and horizontal component in any given vertical plane may be influenced by the orientation of that plane. The two vertical planes considered were the N-S plane and the E-W plane. If there exists a relationship between the vertical and horizontal vectors when the latter is entirely in the N-S direction, and also another relation between them when
the horizontal vector is entirely confined to the E-W direction, then when the pulsation has both N-S and E-W components, the vertical field will be a function of these relations. If the vertical component associated with $X'$ is denoted by $Z_X$, and that associated with $Y'$ be $Z_Y$, then the observed vertical component when $X'$ and $Y'$ components are simultaneously present will be a function of $Z_X$ and $Z_Y$. If an observed pulsation is not confined entirely in either of the vertical planes through $X'$ or $Y'$ it becomes necessary to separate the observed $Z$ into $Z_X$ and $Z_Y$, and to compute separately the ratios $[Z_X/X']$ and $[Z_Y/Y']$ for the event.

To obtain $Z_X'$ from the Hartland data, those events for which $Y'$ (and therefore perhaps $Z_Y$) were small were selected for analysis. This was done by attaching weights to the values of $|Y'/X'|$ for each event. The scheme for fixing the weights, here denoted by $\omega_{Y'}$, for each $|Y'/X'|$ ratio was as follows:

\[
\begin{align*}
|Y'/X'| > 0.6, & \quad \omega_{Y'} = 0; \\
0.4 < |Y'/X'| \leq 0.6, & \quad \omega_{Y'} = 1; \\
0.2 \leq |Y'/X'| \leq 0.4, & \quad \omega_{Y'} = 2; \\
|Y'/X'| < 0.2, & \quad \omega_{Y'} = 3.
\end{align*}
\]

The reliability of the ratio $|Z_X'/X'|$ for each event will clearly depend on the magnitude of $Z$ which, in most cases, was much smaller than $X'$. Because values of $Z$ greater than
0.5 mm had comparatively smaller errors, weights were attached to the observed Z such that the more reliable values had larger weights. The scheme for fixing the weights, \( w_z \), to the values of Z was as follows:

\[
\begin{align*}
Z &> 0.5 \text{ mm} \quad , \quad w_z = 3 \\
0.3 \text{ mm} \leq Z \leq 0.5 \text{ mm} & \quad w_z = 2 \\
Z &< 0.3 \text{ mm} \quad , \quad w_z = 1
\end{align*}
\]

The effective weight, \( w \), for each \( |Z/X'| \) ratio in order to calculate \( |Z_{X'/X}'| \) (value of \( |Z/X'| \) when \( Y' = 0 \)) is given by

\[
w = w_{Y'} X w_z
\]

This parameter was evaluated for each event. The maximum weight for an event was therefore 9. This method effectively rejects from analysis those events for which \( |Y'/X'| > 0.6 \) and attaches less importance to those values of \( |Z/X'| \) for which the error is considerable. If there was more than one event at a given period \( T \), and if the ratio \( |Z/X'\rangle_T \) for the \( i \)th event was \( X_i \) and its weight was \( w_i \), then the weighted value of \( |Z/X'|_T \) (\( Z/X' \) ratio at period \( T \)) was given by \( \overline{X}_T \) where\[
\overline{X}_T = \frac{\sum w_i X_i}{\sum w_i}
\]
and its weight \( w \) was given by

\[
w = \sum w_i \]
It is to be noted that it is the sum of the weights rather than their mean that is taken as the weight of each ratio. This is done in order that more frequently occurring events will have a greater influence than rare events. Events were grouped according to their periods; the period difference between two adjacent groups being 2.5 seconds. The mean $|Z/X'|$ and cumulative weight were then calculated for each group of events.

The above statistical treatment employed for selecting data for the evaluation of $|Z_X'/X'|$ at Hartland was not appropriate for selecting the data for evaluating $|Z_Y'/Y'|$ because the events scaled had on the average bigger amplitudes in $X'$ than in $Y'$. Also the method could not be extended to the treatment of data from the other observatories because of the greater unreliability and paucity of the data. For these, therefore, the ratios $|Z/X'|$ and $|Z/Y'|$ were calculated for all scaled events.

Three months fluxgate recordings at Lerwick Observatory were kindly supplied by Dr. W.F. Stuart of the Meteorology Department of Edingburgh University, from which micropulsation data were processed to supplement the rapid run record data. The ratios $|Z/X'|$, $|Z/Y'|$, and $Z/(X' + Y')^{1/2}$ were evaluated for each event. Unfortunately the times of occurrence of the events were not supplied.
For each observatory, various scatter diagrams were drawn to bring out the general pulsation activity, the vector property of the pulsations in both horizontal and vertical planes and the dependence of these on the period of the pulsations and time of day. These graphs and results are described below.

3.4 Description of Results.

1. Occurrence frequency of pulsations.

As was noted earlier, events analyzed were of very large amplitude and it is possible to argue that these events form a special group of pulsations and may therefore exhibit peculiar characteristics. One way of checking the above statement is to compare the period spectra and diurnal pattern of occurrence of all events analyzed here with those of all micropulsation events at each observatory as observed by Stuart and Usher (1966). Figs. 3.2a, 3.2b and 3.2c show the frequency of occurrence of pulsations versus period at Hartland, Eskdalemuir and Lerwick respectively. To get these plots, period ranges were taken in 10 second intervals. The total number of events occurring in X', in each period range, was plotted against the group period. Only events occurring in X' were considered in order to make this plot comparable with the analysis of the rubidium records (chapter 6).
FIG. 3.2a OCCURRENCE FREQUENCY OF MICROPULSATIONS AT ROYAL GREENWICH OBSERVATORY
HARTLAND PLOTTED AGAINST PERIOD
FIG. 3.2b. OCCURRENCE FREQUENCY OF MICROPULSATIONS AT ESKDALEMUIR PLOTTED AGAINST PERIOD

(b) Eskdalemuir
FIG. 3.2c. FREQUENCY OF OCCURRENCE OF MICROPULSATIONS AT LERWICK PLOTTED AGAINST PERIOD
It will be observed that the maximum frequency of occurrence appears at periods between 33 and 40 seconds at Hartland, and about 32 seconds at Lerwick. Eskdalemuir has two peaks: the major one appears at about 65 seconds and a minor peak at about 25 seconds. The shapes of these curves and the position of the peaks at each observatory are in reasonable agreement with STUART and USHER (1966).

Another parameter studied here which affords immediate comparison between the result of this analysis and those of the above authors is the time occurrence of the events at each observatory. At Hartland, Fig. 3.3a, there is an indication that pulsations occur most frequently between 07.00 and 17.00 GMT and a second group appears mostly between 20.00 and 02.00 GMT with few events between 02.00 and 05.00 GMT. Maximum activity occurs between 09.00 and 14.00 GMT. This trend is apparent at Eskdalemuir, Fig. 3.3b, and Lerwick, Fig. 3.3c. The pulsations occurring between 06.00 and 17.00 GMT are certainly mostly pc's while those between 20.00 and 01.00 GMT are mainly pt's. The above results, except in detail, are not different from those of STUART and USHER. It may therefore be concluded that the type of event studied in this chapter is the same that STUART and USHER studied.
FIG. 3.3a EAST-WEST TO NORTH-SOUTH AMPLITUDE RATIO $\frac{Y}{X}$ OF MICROPULSATION ACTIVITY AT HARTLAND AS FUNCTION OF G.M.T. CROSSES DENOTE RATIOS WITH VALUES GREATER THAN $\frac{3}{2}$
FIG. 3.3b. EAST-WEST TO NORTH-SOUTH AMPLITUDE RATIO $\frac{Y'}{X'}$ OF MICROPULSATION ACTIVITY AT ESKDALEMUIR AS FUNCTION OF G.M.T. CROSSES DENOTE RATIOS WITH VALUES GREATER THAN $\frac{3}{2}$
FIG. 3.3c. EAST-WEST TO NORTH-SOUTH AMPLITUDE RATIO OF MICROPULSATION ACTIVITY AT LERWICK AS FUNCTION OF G.M.T. CROSSES DENOTE RATIOS WITH VALUES GREATER THAN \( \frac{3}{2} \)
2. The vector properties of pulsations in a horizontal plane.

Distinguishing between pt's and pc's by their time of occurrence, all the scatter diagrams in Fig. 3.3a, 3.3b and 3.3c seem to indicate that pt's have comparable amplitudes in X' and Y'. Unfortunately, the paucity of data points for pt events does not warrant a more definite conclusion regarding their state of polarization. At Hartland, Fig. 3.3a, the mean value of \(|Y'/X'|\) for pc events which occurred between 06.00 and 10.00 GMT lies between 0.4 and 0.8. But from 12.00 GMT to 17.00 GMT the mean value of this ratio is clearly less than 0.25. Thus there is a suggestion that the ratio \(|Y'/X'|\) for pc events at Hartland is a maximum between 06.00 and 10.00 GMT and a minimum between 12.00 and 17.00 GMT. This trend is unmistakably present at Eskdalemuir Fig. 3.3b. Here from 06.00 hours til 10.00 hours the micropulsation amplitudes in X' and Y' are comparable and the mean value of the ratio \(|Y'/X'|\) is about 0.8. Between 12.00 and 17.00 GMT, however, the mean of this ratio is clearly less than 0.3. Thus at Hartland as well as at Eskdalemuir, there is a tendency for pulsations which occur in the morning hours to have relatively higher amplitudes in the magnetic E-W plane than those which occur in the afternoons. This result, if confirmed, suggests that the
major axis of the ellipse of polarization in the horizontal plane of these pulsations rotates about the z-axis in the course of the day. The inclination of the major axis to the magnetic meridian plane decreasing from its maximum value in the mornings to a minimum in the afternoon. If no distinction is made between pc's and pt's, then the graphs suggest that starting from midnight, the inclination of the major axis of the ellipse of polarization in the horizontal plane of micropulsations to the meridian plane decreases, and reaches a minimum at about noon after which it increases again. This trend is not obvious from Lerwick data, probably because of its greater unreliability. Figs. 3.4a, 3.4b and 3.4c are scatter diagrams of $|Y'/X'|$ against period at each of the observatories. In the range of periods considered here, there does not seem to be any association between the plane of polarization and the period of the events.

3. The vector property of pulsations in the vertical plane.

a. Hartland Observatory

Fig. 3.5 is a plot of $|Z/X'|$ against the period of events. The scatter is too large to permit any conclusion on the dependence of this ratio on period. This is not unexpected since no account has been taken of the presence of $Y'$. Fig. 3.6 is the graph of the weighted (section 3.3)
FIG. 3.4a. EAST-WEST TO NORTH-SOUTH AMPLITUDE RATIO \( \frac{V_y}{V_x} \) OF MICROPULSATION ACTIVITY AT ROYAL GREENWICH OBSERVATORY HARTLAND PLOTTED AS A FUNCTION OF PERIOD. CROSSES DENOTE RATIOS GREATER THAN \( \frac{3}{2} \)
FIG. 3.4b. EAST-WEST TO NORTH-SOUTH AMPLITUDE RATIO $\left| \frac{Y'}{X'} \right|$ OF MICROPULSATION ACTIVITY AT ESKDALEMUIR PLOTTED AS A FUNCTION OF PERIOD. CROSSES DENOTE RATIOS GREATER THAN $\frac{3}{2}$. 
FIG. 3.4c EAST-WEST TO NORTH-SOUTH AMPLITUDE RATIO $\frac{X_Y}{X_X}$ OF MICROPULSATION ACTIVITY AT LERWICK PLOTTED AS A FUNCTION OF PERIOD. CROSSES DENOTE RATIOS GREATER THAN $\frac{3}{2}$. 
FIG. 3.5. VERTICAL TO NORTH-SOUTH AMPLITUDE RATIO $\frac{\Delta}{\Delta}$ OF MICROPULSATION ACTIVITY AT ROYAL GREENWICH OBSERVATORY HARTLAND AS A FUNCTION OF PERIOD
FIG. 3.6. GRAPH OF WEIGHTED MEAN OF $\frac{2}{X}$ AGAINST PERIOD. THE NUMBER BESIDE EACH DOT REPRESENTS THE WEIGHT FOR THAT POINT.
mean value of $|Z/X'|$ against period for all events. The numbers beside each point represent its weight. The plot represents very nearly a graph of $|Z_X'/X'|$ versus period. It appears that within the range of period considered, $|Z_X'/X'|$ is independent of period. Fig. 3.7 is a histogram of the weight (measure of reliability) against mean $|Z/X'|$. The characteristic mean ratio for Hartland clearly lies between 0.29 and 0.32.

A plot of the ratio of the vertical to the E-W, components of pulsations versus period is shown in Fig. 3.8. Events for which $|Y'/X'| \geq 1.5$ are denoted by crosses and it is these that give a fair estimate of $|Z_Y'/X'|$. Events for which $|Z/Y'|$ is greater than 2.8 are marked by arrows. They represent events with approximately meridian polarization. Though there is a considerable scatter, but if only events marked by crosses are considered it is seen that $|Z/Y'|$ lies between 0.2 and 0.4. These give an estimate of $|Z_Y'/Y'|$ and it appears its mean value is about 0.3. This seems to suggest that $|Z_Y'/Y'|$ is roughly equal to $|Z_X'/X'|$ to within the accuracy of the data. If this is confirmed, it will mean that the vertical components of pulsations at the Royal Greenwich Observatory Hartland bear a fixed ratio to the horizontal components and do not depend on the direction of the horizontal vectors or on the period of the pulsations.
FIG. 3.7. HISTOGRAM OF WEIGHT (MEASURE OF RELIABILITY) AGAINST $\frac{|z|}{x^2}$.
FIG. 3.8. A SCATTER DIAGRAM OF THE VERTICAL TO EAST-WEST COMPONENT OF MICROPULSATION ACTIVITY AT ROYAL GREENWICH OBSERVATORY HARTLAND AS A FUNCTION OF PERIOD. ARROWS STAND FOR EVENTS FOR WHICH \[ \frac{\Delta}{\Delta t} > 2.8 \]. CROSSES STAND FOR EVENTS FOR WHICH \[ \left| \frac{\Delta}{\Delta t} \right| \geq 1.5 \].
To make a very rough check on this, a graph of \( \frac{\sqrt{Z^2 + X^2}}{Y} \) versus period has been drawn in Fig. 3.9. As should be expected the scatter is relatively small. This plot should be considered only as a rough estimate of \( \frac{\sqrt{Z^2 + X^2}}{Y} \) as it does not take into account the phase differences between \( Y \) and \( X \). However, it seems to suggest that the ratio is again approximately 0.3. Thus there is a suggestion that the vertical to horizontal amplitude ratio of micropulsations at Hartland Observatory is 0.3 and is independent of the direction of polarization of the horizontal vector and of the period, if there is no phase difference between the two orthogonal components of the horizontal vector.

b. Eskdalemuir Observatory

A striking feature of the Eskdalemuir records is the relatively small amplitude of the vertical components of the pulsations. It must be remarked that Eskdalemuir has the largest scale value for the Z-component among the three observatories (c.f. Table 3.1). It was estimated that the ratios \( \frac{|Z_X|}{X'} \) and \( \frac{|Z_Y|}{Y'} \) were each less than one tenth. Thus recorded pulsations at Eskdalemuir Observatory are polarized mainly in the horizontal plane.

c. Lerwick Observatory

Fig. 3.10 is a scatter diagram of \( \frac{|Z|}{X'} \) versus period. The dependence of this ratio on the period of pulsations is
FIG. 3.9. VERTICAL TO HORIZONTAL AMPLITUDE RATIO $\frac{z}{\sqrt{y^2 + x^2}}$ OF MICROPULSATION ACTIVITY AT ROYAL GREENWICH OBSERVATORY HARTLAND AS A FUNCTION OF PERIOD.
FIG. 3.10. VERTICAL TO NORTH-SOUTH COMPONENT RATIO OF MICROPULSATION AT PERWICK OBSERVATORY AS A FUNCTION OF PERIOD
evident. The mean of the ratios for pulsations with periods between 30 and 40 seconds is clearly higher than the mean of the same ratios at Hartland (cf. Fig. 3.5). Here the mean lies between 0.6 and 0.9. Thus in the meridian plane the amplitude distribution among the orthogonal components of pulsations is significantly different at the three observatories.

To examine the state of polarization of micropulsations in a plane perpendicular to the magnetic meridian a plot of $|Z/Y'|$ against period was made. This is shown in Fig. 3.11 in which arrows indicate $|Z/Y'|$ ratios greater than 3 and crosses represent events with $|X'/X'| > 1.5$. It is the latter events that need to be considered in estimating $|Z_{Y'}/Y'|$. Considering only these events in Fig. 3.11 it will be observed that the probable value of $|Z_{Y'}/Y'|$ lies between 0 and 0.4. Unfortunately the estimate could not be made better than this because of the small number of events with predominantly E-W polarization. Perhaps the important thing to note here is that $|Z_{X'}/X'|$ and $|Z_{Y'}/Y'|$ seem to be different. This suggests that unlike Hartland, the strength of the vertical component depends on the orientation of the horizontal vector.

Because of the doubts cast on the reliability of micropulsation data obtained from Lerwick rapid run records, some of the above analysis was repeated using three months' data.
FIG. 3.11. VERTICAL TO EAST-WEST AMPLITUDE RATIO $|\frac{Z}{Y}|$ OF MICROPULSATION ACTIVITY AT LERWICK AS FUNCTION OF PERIOD. ARROWS INDICATE EVENTS FOR WHICH THE RATIO IS GREATER THAN 3. CROSSES DENOTE EVENTS WITH $|\frac{Z}{Y}| > 1.5$
(28th Feb - 24th May, 1965) from a fluxgate record. Figs. 3.12a and 3.12b are plots of $|Z/X'|$ versus period and $|Z/(X^2 + Y^2)^{\frac{1}{2}}|$ versus period respectively. In each plot the appropriate ratio increases with increasing frequency, agreeing qualitatively with Fig. 3.10. This suggests that despite the large scale values, useful information regarding the vector property of pulsation can be obtained from observatory rapid run records.

3.5 Simultaneous Events.

Because the time of occurrence of events at each observatory was taken to be when they attained maximum amplitude, only very few events could be identified as being simultaneous at any two of the observatories. In the few cases identified, Lerwick had the highest amplitude in Z. Amplitude ratios of the Z component of micropulsations at Hartland to that at Lerwick ranged from under 0.1 to 0.9. Differences between corresponding horizontal components at the three observatories could not be ascertained with any confidence. There was, however, a slight indication that pulsations at Eskdalemuir had marginally bigger amplitudes in the horizontal components than corresponding simultaneous events at Hartland or Lerwick.
FIG. 3.12b. VERTICAL TO HORIZONTAL AMPLITUDE RATIO OF MICROPULSATION ACTIVITY AT LERWICK (28th FEB.-24th MAY 1965) AS A FUNCTION OF PERIOD. ARROWS INDICATE RATIOS GREATER THAN 1.5.
3.6 Discussion

At each of the observatories the percentage of micropulsation events with bigger amplitudes in the E-W plane than in the meridian plane was greater than 18%. Pulsations of this type polarized in a plane perpendicular to the meridian are not observed with a magnetometer which responds only to variations in the meridian plane such as the rubidium magnetometer. Such a magnetometer therefore only records a fraction of the total number of pulsations occurring at a place where it is installed. From the analysis in this chapter there is an indication that the planes of polarization of micropulsations at Hartland and Eskdalemuir undergo a diurnal change. If the pattern of diurnal variation of the plane of polarization of micropulsations at different locations are different, as they may well be if the pulsations arise from local transient ionospheric currents, it may be expected to give rise to differences in the occurrence frequency and energies associated with pulsations at different locations, which will not be apparent if the pulsations are monitored with magnetometers which respond only to pulsations in a fixed plane. This suggests that it is quite possible that not all of the observed micropulsation characteristic differences at the three British Observatories (STUART and USHER, 1966) may be intrinsic in the micropulsation phenomena.
The greatest difference between the amplitudes of micro-pulsations at the three stations occurs in the vertical component: the vertical to horizontal amplitude ratio was estimated to be less than one tenth at Eskdalemuir, about three tenths at Hartland and about seven tenths at Lerwick for pulsations of about 30 seconds period. At Lerwick this ratio shows a clear frequency dependence increasing with increasing frequency. The analysis in chapter 2 indicated that over a high conducting medium such as the sea, the vertical component is expected to be very small, (curve (C) of Fig. 2.2). Again Fig. 2.5 which shows the relation between the vertical component and the horizontal vector when the former is produced by a lateral conductivity gradient, demands that pulsations of higher frequency have relatively smaller vertical components than pulsations of lower frequency. Thus the presence of a large vertical field component with its frequency dependence is not explicable in terms of conductivity gradient effect or by direct induction in the ocean.

But a large vertical field may be expected at stations in an oceanic island. Consider two islands A and B shown in Fig. 3.13. At great distances from the islands, the electric currents induced in the ocean by the varying external magnetic field are uniform and their effect is to reduce the vertical
FIG.3.13. DISTORTION OF OCEANIC ELECTRIC CURRENTS BY ISLANDS
component of the magnetic variation to a small value compared with the strength of the inducing field. Near the islands, however, the current systems are distorted because of the conductivity contrast between the island and the surrounding ocean. In the region between A and B, the currents will be concentrated in a small region. High current density in this region may easily give rise to large vertical fields, such as that which has been found in the above analysis to exist at Lerwick. It is readily observed from Fig. 3.13 that the strength of the vertical field will vary from place to place on the islands because of the varying current density. This picture appears satisfactory in explaining the presence of relatively large vertical components of pulsations at Lerwick. It is not implied here that all the vertical fields of micropulsations at Lerwick are due to this cause. The suggestion is that this effect seems a probable contributory cause. But how much of this field is due to this cause is unanswered in this chapter.

The existence of a subsurface conductivity anomaly is suspected at Eskdalemuir and it is not known how this affects the data. It also requires further investigation to understand how the moderately high vertical components of micropulsations arise at Hartland. From the results of this chapter, the explanation of this in terms of a coastal effect
is unconvincing because of the seemingly non-dependence of
the vertical to horizontal amplitude ratio on frequency and
the direction of polarization of the pulsations.

Some of the characteristic differences of pulsations at
the three British Observatories reported by STUART and USHER
(1966) may be explained by the findings of this chapter, i.e.
(1) the intensities of the vertical component of pulsations
are not equal at the observatories, (2) the plane of polariza-
tion of micropulsations seems to undergo a diurnal
variation characteristic of each station. The last statement
needs to be investigated further with data from a highly
sensitive magnetometer. An understanding of how the vertical
pulsation fields are produced is also required. A sea effect
intuitively appears to be a probable cause but this is not
confirmed in the above analysis. It is convenient to arrange
for the two problems - the possible variation of the plane
of polarization and the cause of the differences in intensity
of the vertical components of pulsations - to be studied
concurrently.

To undertake this study would be difficult at Eskdalemuir
because of the small value of the vertical component of
pulsations there and the unknown lateral extent of the
underground conductivity anomaly which is reported to exist
there. Lerwick is also not suitable because of the small
size of the island and the probable "island effect." Among
the three observatories, Hartland in S.W. England offers the
best site for studying any sea effect on recorded pulsations.
An understanding of how the recording at the Royal Greenwich
Observatory Hartland is affected by the proximity of the
sea is useful for the following reasons

1. By knowing the magnitude of the sea effect on the
recorded pulsations at the Observatory, it may be
possible to estimate very roughly the effect of the
conductivity anomaly at Eskdalemuir on pulsations
recorded there.

2. It may give an indication of the "island effect" on
the recorded pulsations at Lerwick.

3. It may be possible to infer whether micropulsations
are due to plane waves or not.

4. The contribution of site differences to the observed
characteristic differences in micropulsation activity
at the three British Observatories may be worked out.

5. With the effect of the recording site on the pul-
sations known, it will be possible to test from a
study of the components of the pulsations which, if
any of the theories of the origin of the phenomena
fits the observations.
These arguments indicate the advantages of component measurements of micropulsion activity at places near and far from the sea in the neighbourhood of the Royal Greenwich Observatory, Hartland. It is necessary that the only site differences between the different locations be their relative distance from the sea. These sites should be as much as practicable on a straight line. A highly sensitive magnetometer with a good frequency response is needed if small differences in pulsation amplitudes at different sites are to be resolved. The rest of this thesis described the execution of this project and the results obtained.
CHAPTER 4

INSTRUMENTATION
1.1 Introduction

Previous measurements of micropulsation with mainly total field instruments have shown that a sensitivity of about one tenth of a gamma (1 gamma = $10^{-5}$ gauss) is required. Assuming that the energy of micropulsations is equally divided among its three orthogonal field components it becomes necessary to have an instrumental sensitivity of about 0.06 gamma ($\frac{1}{\sqrt{3}} \times \frac{1}{10}$) if component measurements are to be undertaken. The sensitivity quoted above applies specifically for pulsations of about 30 seconds period. Since the amplitude of a micropulsation decreases with increasing frequency a higher sensitivity is needed for monitoring pulsations with shorter periods. If one instrument is to be used to measure all pulsations in the period range 10 - 120 seconds, one requirement is that the response of the magnetometer must be such that its sensitivity increases with frequency. This is necessary if a constant accuracy is to be maintained at all periods. Other factors to be taken into account in the choice of the magnetometer are the cost, the simplicity of operation, and the need to have a robust instrument. The induction magnetometer which satisfies most of these requirements was therefore constructed specifically for this project. The detectors are cylindrical
mu-metal cored induction coils in which the amplitude of the induced voltage is proportional to the rate of change of the axial geomagnetic field. The induced voltage is amplified by a commercial amplifier, the output of which is fed to a recorder. A block diagram of the magnetometer is shown in Fig. 4.1 and the details of each unit are described below.

4.2 The Design of the Mu-Metal Core

From Faraday's law of electromagnetic induction, the magnitude of the voltage (\(E\) in e.m.u.) induced in a loop whose area is \(A\) placed in a region where the induction is \(\nabla B\) is given by

\[
E = \frac{1}{\mu_0} \int_{\gamma} \mathbf{B} \cdot d\mathbf{A}
\]

(1)

where \(t\) represents time and \(s\) is the bounded surface. The induction \(\nabla B\) is related to the magnetic field \(\nabla H\) by the formula

\[
\nabla B = \mu \nabla H
\]

(2)

where \(\mu\) is the permeability of the space enclosed by the loop. It must be emphasized that \(\nabla H\) in equation (2) is the actual field within the enclosed space which may be different from the ambient field. For instance, if the space enclosed by the coil is occupied by a magnetic material, the free poles on the surface of the material will always produce a
FIG. 4.1. SCHEMATIC DIAGRAM OF THE INDUCTION MAGNETOMETER.
field which is in opposition to the original field within the material. The resulting magnetic field inside the material will therefore be less than that which would have been present if the magnetic material were absent. This demagnetizing effect depends on the geometry of the magnetic material. Now, the demagnetizing field is proportional to the strength of the poles of the magnetized specimen which produce it. Because the pole strength itself is proportional to the intensity of magnetization (I), the demagnetizing field may be represented as NI where N is a constant related to the geometry of the magnetized specimen. Thus if \( \bar{H}_0 \) is the magnetising field when the specimen is absent and \( \bar{H} \) is the actual field inside the material, then

\[
\bar{H} = \bar{H}_0 - NI
\]

For specimens with a very simple geometry, N can be calculated if \( \bar{H} \) is assumed uniform inside the material. For an ellipsoid with semi-axes a, b and c where c is the long axis which is made parallel to the magnetizing field, it can be shown (Maxwell's Treatise on Electricity & Magnetism Vol II) that if \( a = b = \sqrt{1-e^2} c \), then

\[
N = 4 \left( \frac{1}{e^2} - 1 \right) \left( \frac{1}{3} e \ln \frac{1+e}{(1-e)} - 1 \right)
\]

Rods of large length to diameter ratio (l/d) can be treated as ellipsoids. Thus equation (4) enables one to calculate N for cylindrical rods of large length to diameter ratio. Fig. 4.2 is a graph of N against l/d plotted on log-log paper.
FIG. 4.2. DEMAGNETISING FACTOR OF ELLIPSOID, LENGTH $l$, DIAMETER $d$. 

$N = \text{Demagnetising Factor (x10}^8\text{)}$

$l = \text{Length}$

$d = \text{Diameter}$
To estimate the sensitivity of the induction sensor for a given number of turns, we need to know not only the field inside the core but also the effective permeability of the core and its cross-sectional area. As will be discussed later, the permeability of the core varies along its length reaching a maximum value at its mid-point. The effective permeability is here taken as the permeability of the core near its mid-point. Consider a coil of $n$ turns on a cylindrical core with demagnetizing factor $N$, the permeability of whose material is $\mu$ in a given field. The flux ($\Phi$) linking the coil when placed in a uniform field $H_0$ parallel to the core axis is

$$\Phi = n A B$$  \hspace{1cm} (5)$$

where $A$ is the cross-sectional area of the core and $B$ is the uniform induction inside the core corresponding to the internal field $H$. If $K$ (in e.m.u.) is the magnetic susceptibility of the material of the core then the following relations hold

$$I = K H, \quad \mu' = 1 + 4\pi K.$$  

By expressing $I$ in terms of $\mu'$ we obtain from equation (3)

$$H/H_0 = 1/(1 + \frac{\mu' - 1}{\mu' + 1} N) = 1/(1 + \frac{\mu' - 1}{\mu' + 1} \mu')$$ \hspace{1cm} ($\mu' \gg 1$)$$

or

$$B/B_0 = \mu'/(1 + \frac{\mu' - 1}{\mu' + 1} \mu')$$ \hspace{1cm} (6)$$

therefore

$$\Phi = n A H_0 (\frac{\mu'}{1 + \frac{\mu' - 1}{\mu' + 1} \mu'}) \hspace{1cm} (7)$$

$$\frac{3}{2} \frac{\partial \Phi}{\partial t} = n A \frac{\partial}{\partial H} \left( \frac{\mu H}{1 + \frac{\mu' - 1}{\mu' + 1} H} \right) \frac{\partial H}{\partial t} = n A \frac{\partial}{\partial H} (\mu H) \frac{\partial H}{\partial t} \hspace{1cm} (7)$$
If we put \( H_o = H_{oo} + h_o \sin wt \) and make use of (6), then (7) becomes
\[
\frac{\partial (\frac{\partial}{\partial t})}{\partial t} = -\dot{\mathbf{E}} = nA \frac{\partial}{\partial H} (\mu H) \cdot h_o w / (1 + \frac{\mu_n}{\mu}) \cos wt
\]
where
\[
\mu_n = \left(1 + \frac{\mu_n}{\mu}ight) \frac{1}{\partial H} (\mu H) \cdot \frac{1}{\partial H} (\mathbf{B})_H
\]
(9)
is the effective permeability of the core at the given field.

A check on the consistency of this equation is made by noting that if \( N \to 0 \), \( \chi \to \chi^\prime \). If \( n = 10^5 \) turns and \( w = 2\pi (1 \text{ c/s}) \), \( h_o = 1 \text{ gamma} \), then
\[
|\dot{\mathbf{E}}| = \frac{2\pi}{10^2} (A \cdot \mathbf{H}) \cos wt \cdot V
\]
(9a)
As should be expected the sensitivity of the sensor is proportional to the product of the cross-sectional area and the effective permeability of the core.

To evaluate \( \mu \) for a given field \( H \), we need to know the values of \( N, \mu \), and \( \frac{\partial (\mathbf{B} \cdot \mathbf{H})}{\partial H} \). \( N \) is obtained from Fig. 4.2, while \( \mu \) and \( \frac{\partial (\mathbf{B} \cdot \mathbf{H})}{\partial H} \) are found from the magnetization curve for the material of the core. Fig. 4.3 is this curve for Standard Telephones and Cables (S.T.C.) limited permalloy "C". From the technical data sheet for this alloy the maximum permeability \( \mu_{\text{max}} \) is 150,000 and the maximum flux density is \( B_{\text{max}} = 8000 \). Now since \( B = \mu H \), it is necessary
FIG. 4.3 MAGNETIZATION CURVE FOR THE ALLOY OF THE CORE OF THE INDUCTION COIL.
that the magnetic field inside the core be less than 0.05 oersted if the core is to remain unsaturated. A check on whether this condition is satisfied in the presence of the earth's field, 0.5 \text{f}^{-}, is made as follows: The relation between the external (H_{0}) and internal (H) fields is given by \( H = H_{0}/(1 + \frac{\mu N}{4\pi}) \). If H is to be less than 0.05 \text{f}^{-} we must have 0.05 > H_{0}/(1 + \frac{\mu N}{4\pi}). Putting N = 0.0132 (1/d = 60) we obtain \( \mu > 8.6 \times 10^{3} \) if \( H_{0} = 0.5 \text{f}^{-} \). From Table 4.1, showing values of \( \mu \) for various values of H (calculated from Fig. 4.3), the condition is satisfied for all values of H greater than 0.005 \text{f}^{-}. Even if \( H_{0} \) is put equal to 0.7 \text{f}^{-}, the condition for non-saturation of the core becomes \( \mu > 12 \times 10^{3} \), which is also satisfied. Thus for any value of H less than 0.05 \text{f}^{-}, \( \mu \) can be calculated, with the help of equation (9). This has been done for H = 0.02 \text{f}^{-} and \( H_{0} = 0.5 \text{f}^{-} \) and various values of N. The result is shown in Table 4.2. The product \( \mu \cdot A \) increases with decreasing values of 1/d. This table, however, does not take into account the fact that \( \mu \) is not constant along the bar because of the free poles at the ends. The value calculated here is the maximum permeability for the core which is only achieved at the centre of the core. In practice \( \mu \cdot A \) will decrease with decreasing 1/d value. Experiments showed that \( \mu \) was only constant for about half the length of the rod.
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<th>H Oersteds</th>
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Table 4.1

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<th>10</th>
<th>5</th>
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<td>2.0</td>
<td>4.0</td>
<td>10.0</td>
<td>20.0</td>
</tr>
<tr>
<td>A cm²</td>
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<td>0.8</td>
<td>3.0</td>
<td>12.0</td>
<td>78</td>
<td>314</td>
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<td>540</td>
<td>1817</td>
<td>6300</td>
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<td>10000</td>
</tr>
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<td>( \overline{N} )</td>
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<td>195</td>
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<td>2013</td>
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<td>3003</td>
<td>3862</td>
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Table 4.2  \( l = 100 \text{ cms in each case} \)
Among the disadvantages of using a core of small 1/d ratio are

1. The end effect which reduces sensitivity (described in section 4.3) becomes pronounced.

2. For a fixed number of turns of coil, more wire is required for a fixed sensitivity value of the magnetometer. This increases the resistance of the coil and makes the coil bulky.

3. The formula used to evaluate \( N \) is not accurate at a low 1/d ratio.

In deciding the actual dimensions of the core, account was taken of the ease of handling the sensor in the field, the expected sensitivity of the magnetometer and of course the manufacturer's specification of the limits of core dimensions. The dimensions of the core finally chosen were 60 inches in length and one inch in diameter giving a value for \( N \) of 0.0132.

Having fixed the dimensions of the core and hence \( N \), the effective permeability and internal field can be calculated for a given ambient field. The value of \( H \) is obtained graphically from the plot of \( H = H_0/(1 + \mu \frac{\mu - 1}{\mu + 1}) \) with \( H_0 \) set equal to 0.5; \( \mu \) versus \( H \) plot of the material of the core; as is shown in Fig. 4.3b. The operating value of \( H \) is the value at the intersection of the two curves. From
FIG. 4.3b. DETERMINATION OF THE OPERATING POINT OF THE SENSOR.
Fig. 4.3b this is about 0.01. Obviously the value of $\mu$ at the operating point represents the permeability of the alloy at the operating field which is different from $\mu$ at that field. To obtain $\mu$, $\mu'$ and $\left(\frac{\mu}{\mu'}\right)_0$ were read from Fig. 4.3. These were respectively $4.5 \times 10^4$ and $4.7 \times 10^4$. Substituting for these in equation (9) gives $\mu = 970$. This is in fair agreement with the experimentally derived value of 900. The discrepancy is largely due to the errors in the determination of $\left(\frac{\mu}{\mu'}\right)_0$. The experimental determination of $\mu$ consisted of measuring the voltage output from an air cored coil placed in an alternating magnetic field radiated from a low frequency oscillator. The output of the same coil was again measured when the coil was mu-metal cored. The ratio of the latter voltage to the former gave the approximate value for $\mu$. The theoretical value of $\mu A$ is equal to 4930 cgs. Thus with a coil of $10^5$ turns the expected sensitivity of the sensor is from equation (9a), 49 $\mu$V per gamma/sec which is comparable with the experimentally derived value of 37 $\mu$V per gamma/sec. This means that a sinusoidal signal with an amplitude of one gamma and a frequency of one c/s will induce a sinusoidal e.m.f. whose amplitude is about 230 $\mu$V. The agreement between the experimental and theoretical values of the sensitivity is considered satisfactory if it is remembered that no account has been taken
of the finite value of the resistance of the coil and the
errors in the determination of \( \frac{\Delta V}{\Delta t} \). Since the voltage
induced in the coil is proportional to the reciprocal of the
period of the signal, the response of the coil-core system is
easily calculated. This is shown in Fig. 4.4. The increase
in sensitivity with frequency is qualitatively what is
required in order to compensate for the fact that micro-
pulsation amplitudes decrease with increasing frequency.

4.3 Coil Design.

At Hartland, the most frequently occurring pulsation
has a period of about 40 seconds and a total field amplitude
of about half a gamma. The voltage developed in a coil of
10^5 turns by such a pulsation is easily deduced from Fig.
4.4 and is about 3 \( \mu \text{V} \). The measured noise level of the
amplifier unit of the magnetometer was about 1 \( \mu \text{V} \) peak-to-peak.
This gives a signal to noise ratio of about 6 for pulsations
of 40 seconds period.

It is therefore necessary to amplify the voltage
induced in the sensor. Obviously an increase in the number
of turns leads to an increase in the induced voltage. The
consequent increase in resistance of the coil tends to
offset the gain in sensitivity in the following two ways:
(a) The noise due to the coil being proportional to the
FIG. 4.4. THEORETICAL FREQUENCY RESPONSE OF THE SENSOR WHEN A COIL OF $10^5$ TURNS IS USED.
square root of the resistance, increases with increase in the number of turns and therefore reduces the increase in the signal to noise ratio.

(b) Assuming that the input impedance, \( R \), of the amplifier unit of the magnetometer is very much greater than the resistance of the coil, then the coil may be regarded as a voltage source of internal resistance \( \gamma \) ohms. With such an arrangement depicted in Fig. 4.5, the voltage applied to the amplifier is only \( \frac{R}{R+\gamma} \) times the total voltage developed in the coil. Thus while increasing the number of turns of wire increases the voltage developed, it reduces the fraction of it applied to the amplifier.

To achieve a balance between these opposing effects, coils with varying numbers of turns were constructed and the signal to noise ratio was determined for each. Three groups of coils, \((1.0, 2.0, 2.5) \times 10^5\) turns, were constructed. By connecting them in the right order, coils with \((1.0; 2.5; 3.0; 4.0; 4.5; 5.0; 5.5; 6.0; 6.5; 7.0; 7.5) \times 10^5\) turns were made and an appropriate signal to noise ratio for each combination was determined. The inducing signal was provided by a small rotating magnet whose position relative to the coil was fixed. Noise recordings were made by connecting the coils directly to the amplifier and without the mu-metal. Though the differences were not large, \(6 \times 10^5\) turns gave the
FIG. 4.5. EQUIVALENT VOLTAGE SOURCE FOR THE MAGNETOMETER.
highest signal to noise ratio and was therefore adopted as the working value. Enamelled copper wire of 0.0084 inch diameter was used for the winding; the choice of the guage being dictated by the desire to reduce both the weight and resistance of the coil.

Each sensor consisted of three coils, each 7 inches long with $2 \times 10^5$ turns giving a resistance of about $51 \, \Omega$. Each coil was protected against thermo-electric and electro-chemical voltages and moisture by being sealed in epoxy resin. The three coils for a sensor were connected in series and bolted together.

With the above combination of coils the maximum sensitivity expected at any period is that given in Fig. 4.4 multiplied by a factor of 6. Thus a typical pulsation of 40 seconds period and half a gamma in amplitude will induce a varying voltage whose maximum amplitude is about $17 \, \mu V$. The noise level observed with the complete instrument was $3 \, \mu V$ peak-to-peak. For a pulsation of $T$ seconds periods and a gamma in amplitude, in order for it to be observed, it is necessary that

$$ (222 \times 2 \eta H \times a/T) > \frac{3}{2}, $$

i.e. $a/T > \frac{1}{6\eta H}$. The above relation gives the minimum amplitude of an
observable event at any given period. For example if $T = 40$ seconds, then in order that the event be observable, it is necessary that $a > 0.05$ gamma. This is the right order of sensitivity needed for component measurements of micropulsations as was noted in section 4.1.

The experimentally derived values of the sensor sensitivity were in good agreement with the theoretical values only when the coil was fixed near the mid-point of the core. Fig. 4.6 shows the variation of the sensitivity of the sensor with the position of the coil on the core. It is seen that the sensitivity is constant for any position of the coils greater than 35 cms from the ends of the core. Its value was approximately equal to the theoretical value. Outside this range, however, the sensitivity depends on the position of coils on the core. This end effect arises from the fact that the calculated effective permeability only applies to the middle of the core. Towards the ends of the core, the demagnetizing effect of the free poles becomes considerable. Hence the coils were fixed rigidly at the middle of the core with araldite to avoid changes in sensitivity with changes in position.

Since the magnetometer was required to operate continuously for a long time, drift due to thermal effects had to be kept to a minimum. This problem was overcome by
FIG. 4.6. RELATIVE SENSITIVITY OF THE SENSOR AS A FUNCTION OF POSITION OF COIL ON THE CORE.
enclosing the coils in a polythene tube filled with mica fillings which offered satisfactory thermal insulation. Burying the sensors, as described later, at depths at which the temperature fluctuated less than on the earth's surface also assisted in reducing thermal drifts. The detection of voltages of chemical origin by the sensor is another factor that may cause drift. To avoid this, the coils were oven baked and then covered with epoxy resin (araldite). This was not completely successful as was discovered during the field work.

The core-coil system was encased in a polythene tube 6½ inches long and 5⅞ inches in internal diameter. Towards the ends of the core were fixed perforated polythene discs whose function was to stop the sensor from wobbling in the tube. Short cylindrical blocks of polythene were used to cover the ends of the tube and were sealed on to the tube with araldite. The leads from the coils passed through a small hole near one end of the tube, again araldite was used to seal the holes. During the experimental stages the whole arrangement proved water-tight. A schematic cross-section diagram of the whole sensor is shown in Fig. 4.7.

Any motion of the sensor in the earth's magnetic field produces noise: an extremely small rotation in a field of 50,000 gammas or so is equivalent to a signal of several
FIG. 4.7. SCHEMATIC DIAGRAM OF THE CROSS SECTION OF THE SENSOR ARRANGEMENT.
gammas. The mounting of the sensors should therefore prevent any vibrations being communicated to it. At Silwood Park, the Imperial College field station near Ascot, the sensor was buried in the ground at a depth of four feet and left there for about nine months, during which vibrational tests and occasional checks on the sensitivity were made. These tests revealed that burying was a satisfactory way of solving the mounting problem for the horizontal sensors. Because of the high noise level at Silwood Park, particularly in the vertical field, an experimental investigation on the best method of mounting the vertical field sensor could not be carried out. Two weeks experimental study was then made at Sheffield, in November 1964. The field site was the experimental station belonging to the Physics Department of the University of Sheffield. Here the noise level was considerably less than it is at Silwood. The records obtained from here indicated that partial burying of the vertical sensor could be satisfactory if an adequate wind screen was provided. Burying the sensors served a dual purpose: it shielded the sensors from wind vibrations and reduced drift due to temperature changes.
Amplifier

A Hewlett-Packard model 425A DC micro volt-ammeter was employed to amplify the voltage developed in the sensor. It is an extremely sensitive instrument and measures voltages from $1 \mu V$ to one volt and currents of one picoampere to 3 milliamperes. The voltage ranges consist of positive and negative voltages from $10^{-6} V$ full scale to one volt full scale in an eleven step $1, 3, 10$ sequence. It has an input resistance of one megohm. With a coil resistance of about $153 \, \Omega$, only about 85% of the voltage developed in the sensor is actually applied to the amplifier. The maximum gain of the amplifier is $10^4$.

The frequency response of the amplifier and coil is shown in Fig. 4.8. This was obtained by using the amplifier as a DC micro volt-meter to measure the voltage developed in the sensor by the varying field radiated by a low frequency oscillator. Neither the sensor nor the amplifier was connected to the oscillator. The output of the oscillator and the position of the sensor relative to the oscillator remained unchanged during the experiment. Very low sensitive ranges of the voltmeter were employed to measure the voltages so that natural signals were negligibly small. It will be observed that up to 0.5 c/s the frequency response is linear, indicating a constant gain of the amplifier from DC to 0.5 c/s.
FIG. 4.8. FREQUENCY RESPONSE OF THE SENSOR AND AMPLIFIER SYSTEM.
However, signals with frequencies greater than 0.95 c/s are attenuated with increasing attenuation for higher frequencies. The dotted line marked (A) is a continuation of the linear part of the frequency response curve and represents the response the system would have if the amplifier had a constant gain at all frequencies. The fact that the observed sensitivity at frequencies between 0.6 - 0.9 c/s is greater than the expected sensitivity (linear part) for a constant gain of amplifier seems to suggest that the resonance frequency of the system lies in this frequency range. It may not therefore be satisfactory to use the system to monitor magnetic variations with periods less than two seconds.

An estimate of the AC rejection of the amplifier at any frequency is easily made by noting the values of the sensitivities on the curves (A) and (B) at the frequency. If these are respectively $S_A$ and $S_B$ then the AC rejection of the amplifier at that frequency is given by $20 \log_{10} \left( \frac{S_A}{S_B} \right)$ decibels. For example, the value of this at one c/s is 2.5 db. This compares well with the manufacturer's specification of about 3 db at one c/s. At frequencies greater than 1.7 c/s the amplifier output was of the same order as the noise level at Silwood Park, so that responses at these high frequencies could not be measured with any confidence. However, the manufacturer's specification gives the attenuation at 50 c/s
to be at least 50 db. During the field work it was found necessary to have a further rejection at 50 c/s particularly in the vertical field sensors. This was achieved by connecting 0.01 μF capacitor across the input of the amplifier.

Normally connection to the amplifier was via a probe. Since the amplifier was to be used continuously, it was found necessary to order special input cable from the manufacturers in order to reduce thermo-electric effects. The cable was soldered on to the sensor across the 0.01 μF condenser and connected to the amplifier via a socket. When operated alone the noise level was less than 1 μV peak-to-peak. Excessive noise was occasionally produced by poor contacts between the amplifier valve pins and their sockets and failure of the valves, particularly the diodes.

To record pulsations, the output of the amplifier was connected to a recorder and the zero control of both the amplifier and the recorder were adjusted to zero the recorder pen. The amplifier-recorder unit was calibrated by adjusting the output amplitude control of the amplifier to produce the desired deflection on the recorder.

4.5 Recorders

For simultaneous recording of the three components of micropulsations the Record Electrical Graphic recorder was
used. The chart was driven by a synchronous motor whose speed could be set at any of the following speeds: $\frac{1}{3}$", 1", 2", 3", 6" and 12" per minute. Each channel of the triplex recorder had an input impedance of about 2.4 KΩ.

To record a single component of micropulsation, Record portable single channel graphic recorders were used. Though similar in operation, these single channel recorders were different and so were their sensitivities. However, the charts were all driven by synchronous motors similar to that of the triplex recorder. The responses of the recorders were flat at all frequencies below 1 c/s.

4.6 The Calibration of the Magnetometers.

Since the magnetometer measures the time-rate of change of the magnetic field, it is obvious that its sensitivity will depend on the period of the varying magnetic field. Ideally a calibration signal of continuously varying frequency in the frequency range of interest is needed for calibrating the magnetometer. However, there is an indication in Fig. 4.8 that the response of the sensor-amplifier unit is linear over the frequency range 0 to 0.5 c/s. If interest is limited to events with frequencies less than 0.5 c/s then the magnetometer may be calibrated at a limited number of discrete frequencies. Calibration was done during "quiet
periods" when natural and artificial signals were small compared with the calibration signals. At Silwood Park such "quiet periods" occurred around midnight.

The calibration signal was provided by a small rotating magnet of known magnetic moment placed at a measured distance from the sensor which was kept in the broadside position of the magnet. The rotation of the magnet was effected by means of small Rustrack motors, which had no measurable periodic field when they were operating. A system of cog wheels or gears fitted to the motors provided periods of revolution of the magnet of 1.875, 3.75, 7.5, 15, 30, 45, 60, 75, 105, 120 seconds.

In calculating the sensitivity of the magnetometer, it was assumed that the magnetic field due to the rotating magnet was uniform over the whole length of the sensor. The validity of this assumption was verified experimentally as follows: In Fig. 4.9, SON represents the sensor whose midpoint is at O. OB is a perpendicular bisector of SON and B is at a distance \( \gamma \) from O. AB = BC = SO = ON. The magnet was rotated at each of the three positions A, B and C. The field was regarded as uniform over the sensor if the magnetometer outputs were the same when the magnet was rotated at each of the three positions. The minimum value of \( \gamma \) was found to depend on the period of revolution of the
FIG. 4,9. ILLUSTRATION OF A METHOD OF ENSURING THAT THE FIELD DUE TO A ROTATING MAGNET IS UNIFORM OVER THE WHOLE LENGTH OF THE SENSOR (SON).
magnet. All calculations were made with $\gamma$ greater than the minimum value.

Different sensitivities of the magnetometer at any frequency may be achieved by setting the range switch of the amplifier unit to different ranges. This is desirable if pulsations are to be recorded at all levels of pulsation activity. During the recording of the three components of micropulsations, experience showed that only two ranges of the amplifier were needed: a setting on .100 $\mu$V f.s.d. was found satisfactory for recording the horizontal components while the recording of the vertical component required setting the amplifier on 30 $\mu$V f.s.d. Calibration curves of the magnetometer for these two sensitivity settings are shown in Figs. 4.10 and 4.11. It was found more convenient to express the sensitivity in units of gammas per chart line rather than in microvolts per gamma as was done during the testing stage of the magnetometer. The Triplex recorder was used for the simultaneous recording of pulsation components. The magnetometer sensitivity corresponding to 100 $\mu$V f.s.d. setting of the amplifier is here referred to as the low sensitivity while the 30 $\mu$V f.s.d. setting of the amplifier corresponds to the high sensitivity setting of the magnetometer. The ratio of the two sensitivities at all periods is approximately equal to the expected value of 3.3. At the
FIG. 4.11. HIGH SENSITIVITY CALIBRATION CURVE OF THE INDUCTION MAGNETOMETER WHEN THE TRIPLEX RECORDER IS USED.
high sensitivity setting of the magnetometer the noise level was less than one chart line (≈ 1.2 mm), thus giving a high signal-to-noise ratio for pulsations with amplitudes of over ten chart lines. At the low sensitivity setting, the noise was almost undetectable. In the units of sensitivity adopted, the smallest detectable amplitude of an event was of half a chart line amplitude. For pulsations of 30 seconds period it is found from Fig. 4.11 that the minimum amplitude of the event is 0.03 gamma.

Obviously the unit in which the sensitivity was expressed had some disadvantages: it depended on the chart paper used and therefore different chart papers require separate calibrations. Thus when single channel recorders were used for recording the single components of pulsations, a calibration curve for each recorder was necessary. Figs. 4.12 and 4.13 were calibration curves for the single component induction magnetometers used to record pulsations at Shebbear and the Royal Greenwich Observatory, Hartland. Because the recorders were not quite identical in their frequency response the curves are not quite identical in form. It will be observed from Fig. 4.12 that the recorder stationed at Shebbear had a sluggish response at periods less than five seconds.
FIG. 4.12. CALIBRATION CURVE OF THE SINGLE COMPONENT INDUCTION MAGNETOMETER STATIONED AT SHEBBEAR.  

Gammas per chart line  

Period in seconds
FIG. 4.13. CALIBRATION CURVE OF THE INDUCTION MAGNETOMETER STATIONED AT ROYAL GREENWICH OBSERVATORY, HARTLAND.
To compare the performance of the three different recorders used and make a check on the relative sensitivities of the magnetometers, the three sensors were placed with their axes parallel to the N-S direction and as far apart as space allowed in one of the Royal Greenwich Observatory test blocks. Recording of geomagnetic variations was made for 24 hours. The record obtained was examined for any phase and amplitude differences. For all events which occurred the amplitudes recorded by the three magnetometers showed 92% agreement at all periods which ranged from 20 to 130 seconds. The 8% difference was thought to be due to coupling between sensors. A short length of record obtained when two of the sensors were kept in different buildings over 50 yards apart supported the above conclusion. For very regular events there was no measurable phase difference between the three traces. Lastly one of the sensors was set in the direction of the total magnetic field to record micropulsations. The record obtained was compared with that of the rubidium magnetometer. Agreement between the two was very good.
CHAPTER 5

FIELD WORK
5.1 Introduction

An investigation of micropulsation phenomena at three British Observatories – Lerwick (Shetland), Eskdalemuir (Scotland) and Hartland (Devon) – (STUART and USHER, 1966) shows that important differences exist between the characteristic properties of the pulsations at each station. It was observed that the period and the time of occurrence of the most frequently occurring pulsations are different at these stations and also the energy is significantly different.

In chapter 3, a large amount of micropulsation data from the quick run magnetograms from each of the observatories was used to make a rough comparison of the pulsation vector characteristics at the three observatories. A significant difference was noted between the vector properties of these pulsations at the three stations. Also at each station, there is an indication that in a horizontal plane the micropulsation vector undergoes a diurnal change. A confirmation of this is very desirable.

From the theoretical considerations in chapter 2, it is apparent that certain geological situations will affect both the energy and the vector structure of the recorded pulsation. Also a possible amplification of certain micropulsation frequencies may lead to an erroneous conclusion concerning
the most frequently occurring micropulsation event at each station. Therefore before comparing micropulsation activities at the three observatories and the actual observations with theory, it is necessary that the effect of the differences in recording sites be at least approximately known. The most obviously significant site difference between the observatories is their relative distance from the sea. Thus an investigation of the vector properties of pulsations in the neighbourhood of one of the observatories, with recording sites located closer to and much farther from the sea than the observatory itself will give an indication of any sea-land boundary effect. Ideally a straight coast is required in order to study the "coastal effect." However, the nearest sea coast to each of the three observatories is far from being straight. For a study on the land side of the coast, it is desirable that the geology of the area be as simple as possible and devoid of geological situations such as faults, dykes and heavily folded structures, etc., which may be expected individually to give rise to perturbations of the incident electromagnetic waves. From these considerations and those discussed in chapter 3, of the three observatories, Hartland in S.W. England offers the best approximation to the ideal requirement and was therefore chosen as the area to carry out this investigation. Below are described in some detail
the geology of the area, the field sites, recording procedure and the difficulties encountered during the data collection.

5.2 The Geology of Central Devon and North Cornwall.

Fig. 5.1 is a geological map of part of Devon and a part of North Cornwall. Central Devon, which includes the Hartland area, and North Cornwall as seen in Fig. 5.1 are underlain by rocks of Carboniferous age known as the Culm Measures which occupy an area of more than 1200 square miles. Their northern outcrop extends eastward near Barnstaple to west of Wellington in Somerset; the southern outcrop extends from Boscastle to the east of Dartmoor. The Culm Measures consist principally of shales and sandstones with rare traces of limestones. Bordering on a part of the southern and southeastern margin of this expanse are the granitic rocks of Dartmoor. Also not far removed from its southwestern margin are the Bodmin rocks of igneous origin. In the east towards Exeter the Culm Measure is terminated by Permian rocks consisting mainly of sandstones. The northern region gives way to rocks of Upper Devonian age which are mainly slates with thin beds of limestone and sandstone. The beds pass gradually into the Carboniferous shales and there is no definite line of demarcation between the two different rock types. Thus there is no sharp conductivity contrast between the two
FIG. 5.1. A SKETCH GEOLOGY MAP OF PARTS OF DEVON AND CORNWALL.
different outcrops and pulsations recorded in the neighbour-
hood of the northern margin of the Culm Measures are not
expected to be appreciably affected by this change of rock
type.

Rocks of upper Devonian age also replace the Culm
Measure at its southern boundary. They consist mainly of
shales and sandstone which have been metamorphosed, particularly
along the coast. Unfortunately there is no available infor-
mation about the subsurface geology of this area. If the
rocks below the Culm Measure area may be assumed uniform, it
means that it is only at the boundary with the other surface
rock types that sharp conductivity contrasts may be expected.

5.3 The Choice of Recording Site.

In order to relate the vector properties of micro-
pulsations in S.W. England with those at Eskdalemuir and
Lerwick, it is necessary that the Royal Greenwich Observatory
Hartland be one of the recording stations. A further
advantage of having the Hartland Observatory for a recording
site is that a direct comparison can be made between the
induction magnetometer records and those of the rubidium
magnetometer which was kept operating at the observatory
throughout the period of field work. At such times when there
were pulsations of large amplitude, a direct comparison between
the induction magnetometer, the rubidium magnetometer and the Observatory rapid run records was helpful.

The influence of the land-sea boundary on the recorded geomagnetic pulsations at the Observatory may be ascertained by studying the recordings made at sites much nearer to and much farther from the sea-land boundary than the Observatory site. From the view point of micropulsations the effective coastline will be located some distance out to sea because of the shelving ocean floor. It would therefore seem that a recording station sited some distance out to sea such as at Lundy Island, north-west of Hartland Point (Fig. 5.1) would be desirable. However, recordings made at any site on a small island such as Lundy may not be representative of the undisturbed geomagnetic variation of the locality because of the phenomenon of island effect (MASON, 1963). Thus the nearest we can get to the effective coastline from the land side of the boundary is the geographical sea coast. The Royal Air Force (R.A.F.) Station at Hartland Point provided a suitable site. This is roughly two miles due North-west of Hartland village. The R.A.F. Camp is out of bounds to the general public, but permission was obtained to record there. On the land side, the camp is surrounded by farm lands and there are few farm houses between the camp and Hartland village. The absence of interfering signals from outside the
camp is a great advantage at this site. However, at the camp itself there are a number of radar installations and as will be seen later they were sources of interference. From a rough comparison of the recordings at the Observatory and at Hartland Point, it was not considered necessary to site further recording stations between the two sites.

In choosing recording sites much farther from the sea than the observatory, account was taken of the availability of power supply, level of interference and distance to places where a sharp conductivity contrast was expected to exist. The necessity of using mains supply restricted recording stations to near villages, farm houses and public institutions such as schools and hospitals. Unfortunately, around many of these places the noise level was high presumably because of traffic along the roads, overhead electric power cables and the domestic use of electricity. The magnetometer was particularly sensitive to changes in the loading of power cables even when the sensor was as much as a hundred yards away. Recordings in the neighbourhood of transformer installations had to be avoided if interference from 50 c/s was to be kept to a minimum. Taking advantage of the generosity of the local farmers who allowed us use of their domestic power supply, test recordings were made at isolated farm houses. They proved noisy; the milking machine
contributing, at times, to the general noise level. This fact and the undesirability of having power cables across peoples living rooms restricted our choice of field site to public places. To be of any use such a place must be comparatively large, such that some part of it is far removed from sources of interference. Such a condition was found at Shebbear College about 15 miles South-east of the Observatory and a few miles south of Torrington. It is situated in an agricultural district and is far removed from roads carrying heavy traffic and other major sources of interference. Permission was granted for the magnetometer to be installed on the college field far removed from the college offices. The nearest boys' dormitory from which power was obtained was some 75 yards away. The nearest arable land was more than 100 yards away. A test recording showed that the noise level was satisfactorily low.

In studying at more than one station, the spatial characteristics of the micropulsation components and the effect of a particular geological situation on them, it is desirable to ensure that the site geology of the recording stations is approximately similar. In particular, places where large conductivity contrasts occur between adjacent rock types must be avoided. A study of Fig. 5.1 and the resistivity of the rocks concerned (JAKSOKY, 1961) leads us
to expect that in addition to the coastal boundaries of the area being investigated, a large conductivity contrast may exist at the southern and south-eastern boundary of the Culm Measures, where the Carboniferous rocks abut on the granitic rocks of Bodmin Moor and Dartmoor. It must be pointed out that the expected perturbations of the magnetic variations at these places are much smaller than that at the sea-land boundary. However, to ensure that the distance from the chosen recording site to the nearest sea coast is much smaller than from the Culm Measure - granite boundary from the recording station, it was thought undesirable to site recording stations South of Hartland towards the Bodmin Moor or South-east beyond Shebbear. It is to be noted that any station south of Shebbear may experience the undesirable and unpredictable influence of several distinct sea coasts. It was not possible to find a recording station between Shebbear and Hartland and it was not proved necessary, because the results from these sites provided sufficient conclusions about the effect of the sea-coast on recorded geomagnetic micropulsations at the Royal Greenwich Observatory Hartland. The position of Hartland village, Hartland Point and Shebbear in relations to the sea coast and local geology is shown in Fig. 5.1.
The Simultaneous Recording of the Three Components of Pulsations at the Observatory.

The installation of the sensors presented no difficulty here for the recordings were made in one of the test buildings of the Observatory in which the floor tiles were accurately laid with their edges parallel to the geographic N-S and E-W directions. Since the building had a substantial concrete base, the burying of the sensors was not necessary. One sensor was placed with its axis in the N-S direction and another with its axis pointing E-W. Non-magnetic brick blocks were placed along the polythene tube to stop it from rolling. The vertical component sensor was stood on end at a corner of the building but not in contact with the wall. It was necessary to ensure that there was no measurable coupling between the sensors. This was done by noting the output from each sensor when a small magnet, at a fixed point in the room, was rotated and the other sensors were removed from the room. Inductive coupling between the sensors was negligible if there was no measurable difference between the output of each sensor when other sensors were in position and when they were removed from the room. Of course, this test could only be carried out around midnight when the natural signals were entirely absent or negligibly small. To determine the sense of the field variation a small magnet whose axis is held
horizontal and perpendicular to the axis of the sensor is suddenly turned to lie parallel with the axis of the sensor and with the north pole of the magnet pointing in the positive direction of the sensor. The positive direction of the sensors were defined to be towards the North in the case of the sensor installed in the N-S direction; towards the East for the sensor with its axis along the E-W direction; and vertically down for the vertical component detector. The connection between each amplifier and the three channel recorder was arranged so that a spike appeared on the right hand side of the chart paper when the magnet was turned as described above.

All the three magnetometers were operated on the high sensitivity channel. This meant setting the amplifier on the 30\muV/f.s.d. range. The amplifiers and the recorder were placed on a non magnetic box. The chart speed was set at half an inch per minute. This required changing the chart once a day. Except for occasional flushing of the writing pens and refilling of the inkwells, the magnetometers required little attention here. During magnetic storms or intense magnetic disturbance, the magnetometer had to be left running on the low sensitivity ranges. Recording lasted from March 3rd until March 29th, 1966. There were quite a lot of spikes on the records; mostly due to the thermostat switching of the
heating current of the rubidium magnetometer which was in a hut about 50 yards from the block which housed the sensor. The chart paper was usually changed about 10.00 GMT, but because of occasional paper jams charts were sometimes changed at other times of the day.

5.5 The Simultaneous Recording of the Three Pulsation Components at Hartland Point.

The recording at Hartland Point was made at the R.A.F. Camp. A number of radar installations at the camp were in operation for most of each day excluding the weekends. Because of their high frequency the radar signals were not picked up by the detectors and thus did not interfere with the natural electromagnetic signals in the frequency range of interest. However, there was magnetic interference due to the rotation of iron parts of the revolving section of the radar installations. Test recordings were made to find an area of the camp where this interference was a minimum. This was found in the eastern corner of the camp. Fortunately this part of the camp is remote from the office blocks, road, camp golf course and other sources of interference. Above all it was less than 200 yards from the nearest sea coast. The only disadvantage in this area of the camp was the distance from any source of electricity supply. The power supply for
the magnetometers was obtained from the iron-head of the nearest radar installation. This necessitated the use of power cable about 200 yards long. About 80 yards away from the region of minimum interference and towards the nearest radar installation was a plinth built over a concrete floor more than five feet thick. With its thick walls and floor, the plinth was ideal for protecting the sensors from wind and vibrational motion due to microseisms of both natural and mad-made origin. Unfortunately, because of its small dimensions the plinth could not accommodate more than one sensor and the recording equipment. During the test recording, it was observed that the interfering signal from the radar installation was confined exclusively in a horizontal plane and mainly in the magnetic E-W direction. This meant that the Z-detector could be installed inside the plinth without any fear of increased interference from the radar equipment. In the region of minimum interference, the horizontal field detectors were each buried at a depth of four feet, their axes being positioned by means of a magnetic compass. As at the Observatory, the horizontal distance between the two sensors was such that there was no measurable coupling effect between them. The amplifier and power board serving the horizontal field detectors were housed in a non-magnetic box at a distance of about five yards from each detector. The box had a weather
proof cover and was partly buried to protect it from the strong gales from the sea. Inside the plinth there was another non-magnetic box inside which were the recorder and amplifier for the vertical field detector. Cables connecting the horizontal detectors to their amplifiers and those connecting the amplifiers to the recorder were buried along their entire length to avoid wind movements and the cables being walked over by people.

In normal use, the horizontal field magnetometers were set on low sensitivity range while the vertical field magnetometer was operated at the high sensitivity range. Fig. 5.2 is a trace of a part of a record obtained during a very quiet period. The regular pulsations on the E-W trace is the interfering signal from a radar equipment. All the magnetometers were purposely set on the high sensitivity range to illustrate the magnitude of the interfering signal. Notice that it is not present in the other traces. With the horizontal magnetometers set on low sensitivity ranges the interfering signal is less than half a chart line peak-to-peak and is therefore negligible. Being very close to the sea, the air in the neighbourhood was very damp. This resulted in the chart paper jamming every few hours on the first day of the recording. A great improvement in the situation resulted when a 45 watt electric bulb was installed inside the box housing the recorder.
Fig. 5.2: Illustrating the noise level at Hartland Point.
It was found that the amplifiers were very sluggish in their response. A test showed that this was due to excessive high voltage which was in use for the radar equipment. A series resistor was used to drop the voltage to the normal operating value. Recording lasted from the 29th March until 30th April, 1966.

5.6 The Simultaneous Recording of the Three Components of Pulsations at Shebbear College.

At Shebbear, there was unfortunately no building in which any of the sensors or the recording equipment could be conveniently housed. All installations were made in the open field. As at Hartland Point the horizontal field detectors were buried to a depth of four feet. The polythene cylinder containing the Z-sensor was buried to a depth of four and a half feet so that one foot of it stood above the ground. A dexion frame was constructed over the cylinder and a weather proof cover was then placed over the frame. Loose earth was used to cover the lower end of the weather proof cover. This simple arrangement was sufficient to screen the sensor from mild winds. During strong gales, however, it proved inadequate and wind effects could be observed on the records as spikes. The amplifiers and the recorder were inside a non-magnetic box covered with a weather proof cover. A second box, also
in a weather proof cover, contained spare parts for the magnetometers and odd bits of equipment for on-the-spot repair. As at other places adequate precautions were taken to minimise 50 c/s pick up. Instrumental repairs and daily changing of chart paper in the first two weeks were made difficult and unpleasant particularly during very bad weather by the lack of shelter. Later on a small hut was erected to house the instrument box. Precautions similar to that at Hartland Point was taken to avoid paper jams. The ground in which the sensor was buried was often water-logged. This hastened the flaking off of the araldite used to seal the ends of the polythene cylinder. This led to the development of a voltage inside the sensor. Often this was big enough to make the amplifiers go off scale. Obviously the origin of the voltage was electrochemical in nature but the details of its generation was not known. Repair was effected by replacing the damp mica and sealing the cylinder once again with araldite. Later on, Bostick was used in place of araldite and it proved more effective. As at other stations, a regular check was made on the sensitivity of the magnetometers by measuring their output when a small magnet was rotated. No measurable change in the sensitivity of any of the magnetometers was detected. The paper speed was half an inch per minute as at other stations. Recording lasted from the 30th
April till 14th June. A longer recording period was necessary because micropulsation activity was rather low in May. In quality the records from Sheebbear were poorer than those from Hartland Point. Interfering signals arising mainly from switching electric appliances in a nearby caravan and in the students hostel were recognizable on the traces as spikes. Fortunately the spikes occurred mostly on nights when there was usually little activity. Electricity supply for the magnetometers was obtained from the hostel.

A consistent convention regarding the direction of positive field changes was maintained at all stations. Care was taken, at each station, to ensure that the output from a particular sensor was always applied to a particular amplifier which in turn was always connected to a particular channel of the Triplex recorder. This ensured that the characteristics of each of the magnetometers remained the same at all stations.

5.7 The Simultaneous Recording of Pulsations at All Stations.

The final phase of the field work consisted of recording simultaneously at the three sites each of the three components of micropulsations. As above care was taken to ensure that a common convention concerning the direction of positive field increase was maintained throughout the period of recording of a particular component. At Sheebbear and at the Observatory
single channel recorders were used, but at Hartland Point a channel of the Triplex recorder was used owing to the early discovery that the single channel recorder intended for there was so heavily damped that it could not respond very well to the short period signals. Though the recorders were of different designs, each was calibrated by means of the output amplitude control of the amplifier to which it was connected, to make a given signal produce approximately equal output on the recorders. This allowed easy visual comparison of the records in the field. Because of the high level of micro-pulsation activity towards the end of June and the rest of July, the average recording time for each of the three components was short. The date of recording of each component was as shown below:

<table>
<thead>
<tr>
<th>Component</th>
<th>Date of recording</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>15th - 28th June</td>
</tr>
<tr>
<td>N-S</td>
<td>28th June - 7th July</td>
</tr>
<tr>
<td>E-W</td>
<td>7th - 18th July</td>
</tr>
</tbody>
</table>

From Hartland to Shebbear is about 20 miles by road, while Hartland Point is just under three miles from Hartland village. Owing to the many breakdowns of the motor bike which had to be used to get to field stations, at least once each day, it was not possible to have a fixed time for changing the charts. However, there was hardly any recording time
lost because of this. Instrumental repairs caused no significant loss of recording time. It was the practice to prepare a recording site well in advance of the date of the installation of the magnetometers. In this way only a few recording hours were lost during the move of the instruments from one site to the other. On a number of occasions a local carrier was hired to transport the recording equipment.

5.8 General Remarks.
All the recorders were operated at a chart speed of half an inch per minute which was found to be satisfactory in recording pulsations whose period was greater than two seconds. Included in the daily routine during the field work was the marking on the record, the time when the recording was started and when it ended. The time was read from a watch which was compared with the Observatory standard clock each morning. To obtain the time of an event required knowing the length of the chart from either the time mark at the beginning or at the end of the record. At the end of the day, time was marked along the whole record at intervals of 30 minutes. All checks showed that the speed of the recorders remained constant to better than five seconds in 24 hours.
The parameters of interest at each location are the variation of the pulsation vector in the horizontal and vertical planes and the relation between two corresponding vectors at any two locations. During the period of field work very rough estimates of these parameters were made which were plotted on a rough scatter diagram of the particular parameter against GMT or period. Recording was discontinued whenever a rough trend was indicated by the scatter diagram. The duration of the recording time therefore very much depended on the level of pulsation activity. Micropulsation activity was particularly low in May. This is the explanation for the long time it took in recording the three components at Shebbear.

There were a number of spikes on some of the records particularly the Z-traces at Shebbear and the Observatory. As was remarked earlier, these were mainly due to switching surges or interfering signals of moving magnetic materials in the neighbourhood. The occasional mowing of grass in the vicinity of the magnetometers caused the loss of some recording hours at all the sites. The Hartland Point record was of particularly high quality because of its remoteness from built-up areas. However, during the simultaneous recording of single components of pulsations at all sites, when the Hartland Point magnetometer had to be on high
sensitivity range, interference on the E-W trace arising from the radar installation masked events whose peak-to-peak amplitude was about one chart line. Fig. 5.3 shows traces of samples of records taken at each of the three sites; obviously the records were taken on different dates. It will be noted that at Hartland Point, the trace is almost ruler straight in the absence of pulsation activity while at the other locations the background noise is less than half a chart line peak-to-peak in the absence of spikes. Fig. 5.4 shows traces of simultaneous records of the same event taken at the three stations. The sensitivities of the magnetometers were about the same.

Throughout the period of field work, a rubidium magnetometer was kept in continuous operation at the Observatory. It was a daily routine to make a qualitative comparison between the induction magnetometer records and those of the rubidium magnetometer. When the correspondence between the two records seemed doubtful, an additional check was made by comparing the induction magnetometer and those of the Observatory quick run records. It is important to note that the rubidium magnetometer is very insensitive to pulsations confined entirely in the E-W direction. The explanation of this is given in the next chapter. Comparison of the induction magnetometer records with the standard magnetometer records was thought to be necessary in order to eliminate
FIG 5.3 TRACES OF SECTIONS OF RECORDS ILLUSTRATING THE QUALITY OF RECORDS AT EACH STATION DURING: (a) QUIET PERIOD; (b) ACTIVE PERIOD.
FIG. 5.4. TRACES OF SECTIONS OF RECORDS TO ILLUSTRATE THE QUALITY OF THE SINGLE CHANNEL RECORDS.
**FIG 5.5** ILLUSTRATING AN EVENT NOT PRESENT IN THE RUBIDIUM AND OBSERVATORY RECORD.
from the analysis any pulsations which might arise from vibrational motion due to microseisms of both natural and man-made origins and other causes. Only once was there a continuous pulsation which was not present in either rubidium or Observatory records. It was on 25th April, 1966 and lasted for over two hours between 13.30 to 15.40. Fig. 5.5 is a photograph of a section of this record which was taken at Hartland Point. This event was only in the E-W trace and the period is about 2.5 seconds.

Because the frequency is close to the suspected resonant frequency of the magnetometer (chapter 4), it is likely that the pulsations are instrumental. For this reason they were left out in the analysis. It must be pointed out that even if the pulsations were genuine they would not have shown in the rubidium record, partly because the rubidium magnetometer counter does not respond to such fast events and partly because the events are confined in a plane perpendicular to the magnetic meridian.
CHAPTER 6

RECORD ANALYSIS, RESULTS AND CONCLUSIONS
6.1 Introduction

The measurement of micropulsation activity at the three British Observatories with rubidium magnetometers has revealed characteristic differences between pulsations occurring at each location. The rubidium magnetometer produces measurements of the total field magnitude, $|F_1|$. It is useful to consider how the conclusions from the data obtained with it may be affected by this property. Denote the total magnetic field at a recording station by $F$ and at some instant let its value be $F_1$. After a short interval let the field change to $F_2$. The total field change, $\Delta F$, is given by

$$\Delta F = F_2 - F_1.$$

If it be assumed that $\Delta F$ is a result of a field change $\Delta F_1$ in the direction of the total field, $F_1$, and a field change $\Delta D$ in the plane perpendicular to the meridian, then

$$F_2 = \left[(F_1 + \Delta F_1)^2 + (\Delta D)^2\right]^{1/2}$$

and

$$|\Delta F| = \left[(F_1 + \Delta F_1)^2 + (\Delta D)^2\right]^{1/2} - F_1 \quad (1)$$

Now, consider the case when $\Delta D$ is zero. The field change recorded by the magnetometer is exactly $\Delta F_1$ without any modification. But if $\Delta F_1$ is zero, then $|\Delta F|$ becomes

$$|\Delta F| \approx F_1(1 + \frac{1}{2} \frac{(\Delta D)^2}{F_1}) - F_1 \approx \frac{1}{2} \left(\frac{\Delta D}{F_1}\right)^2.$$
For a field change of one gamma in a plane perpendicular to the meridian, the scalar field change seen by the magnetometer will be approximately $10^{-5}$ gammas (since $F_1 \approx 50,000 \gamma$) which cannot be detected by it. For a simultaneous change of $\Delta F_1$ and $\Delta D$, then from equation (1), $\Delta F$ becomes

$$|\Delta F| \approx \Delta F_1 + \frac{1}{2} (\Delta D)^2 / F_1 \approx \Delta F_1.$$ 

Thus it is clear that measurements using the rubidium magnetometer detect micropulsation activity in the meridian plane only.

Again if $\Delta F_1$ is resolved into its horizontal component $\Delta H_1$ and vertical component $\Delta Z_1$, and if $I$ is the angle of dip at the observing station, then

$$\Delta F = \Delta F_1 = \Delta H_1 \cos I \pm \Delta Z_1 \sin I.$$ 

In the United Kingdom where $I$ is about 70° this gives

$$F = 0.34 \Delta H_1 \pm 0.94 \Delta Z_1.$$ 

Thus the magnetometer is more sensitive to vertical field change than to horizontal field variations. It is obvious therefore that if for some reason the vector character of pulsations varies from place to place, then a study with a total field instrument such as the rubidium magnetometer may lead to erroneous conclusions. It was observed in chapter 3 that such a variation exists at the three United Kingdom Observatories, but it was not possible to attribute the observed characteristic differences to this mainly
because of the inaccuracy of the data used. In measuring the
pulsations analyzed in this chapter, the object was to examine
how the data obtained with a rubidium magnetometer was
affected by the differences in the vector properties of
micropulsations at the three observatories. In particular
it was thought necessary to check, using more reliable data,
the inference in chapter 3 regarding the diurnal character
of the plane of polarization of micropulsations. Also it
was thought that measurements of pulsations near and far
from the sea-land boundary would provide results sufficient
to determine whether some of the vector differences of the
pulsations between the observatories can be attributed to
site differences. Knowing the approximate effect of the
site differences on the recorded pulsations, a comparison
of observations with the existing theories of the origin of
pulsations could then be made. As was discussed in chapter 3,
S.W. England was chosen as a place to undertake the study
because it was thought to be the least affected by undesirable
factors.

6.2 The Analysis of the Field Data.

One of the confusing features of micropulsations is the
high degree of variability in all parameters: it is not easy
to obtain a representative sample record of micropulsations
when, in addition to spatial variations, hourly, diurnal, seasonal and annual variations of activity exist. To reveal any general characteristic thus requires a large amount of observational data. If the different events are to be distinguished and their quality taken into account, manual analysis is a necessary first step. When this is done, specific problems brought out by the general manual analysis may then be examined in greater detail by means of a computer. This is desirable if there is to be no waste of computer time. If computer analysis is to be undertaken, it is necessary that the record be sampled at least twice in the time interval equal to the shortest period present in the record (sampling theorem: Information theory by Goldman, 1958). If the record is in analogue form (as it is here), the use of a computer therefore requires the digitization of the records at an appropriate time interval. This becomes very laborious when up to five months records are analyzed. Perhaps a solution to this problem may be to have two outputs from the magnetometer: an analogue output for manual analysis permitting the selection of events to be analyzed by computer techniques; a digital output, portions of which may be used as a direct input to a computer. Computer analysis was only used here to make a check on the reliability of the technique of the manual processing and its use has been suggested to test one of the conclusions from the general analysis.
Before performing the analysis, a general inspection of the records was undertaken to determine what factors apart from the obvious ones such as local time etc., affect the general appearance of the pulsations. Intermodulation between signals of different period was often observed. It is important to have a criterion for determining whether a series of pulsations which appears and disappears along a record may be regarded as separate events. A comparison of the induction magnetometer records with those of the rubidium magnetometer and the observatory indicates that events with periods greater than about 200 seconds were undetected by the induction magnetometer. To add a safety factor, 240 seconds was taken as the greatest period of an event that could be detected. Thus any detectable single event which was amplitude modulated would have a modulation period of less than 240 seconds. Now, if there are two beating pulsations of periods $T_1$ and $T_2$, then their beat period will be given by $T_1T_2/(T_1 - T_2)$. Two separate trains of pulsations are therefore considered to be the same event if (a) the period of the pulsations in each train are the same, (b) the time separation between the end of one series and the commencement of the other series is less than the greater of the two quantities - 240 seconds, $T_1T_2/(T_1-T_2)$, where $T_1$ and $T_2$ are the periods of the two pulsations present
in each train. Thus pulsations lasting several hours but with zero amplitude for intervals greater than 240 seconds would be counted as consisting of more than one event.

An event qualified for analysis if it had at least three full cycles. Records were scaled by hand and the computations were done on an electronic desk calculator. The parameters measured are defined and discussed below.

1. **Period (T)**

This was defined as the mean of the time interval between adjacent peaks in a series of pulsation and was measured with a scale graduated in five seconds. Though it was possible to determine the time interval between adjacent peaks with an accuracy of ±2 seconds, the variation of the time interval between adjacent peaks from one cycle to another made the overall accuracy in the period determination worse than this. Depending on the variability of the "period" along the train of waves, the period attributed to an event may be in error by as much as five seconds. When a particular train of pulsations showed much variability in period, it was broken into events of constant period such that the error was not greater than five seconds.

2. **Amplitude**

The amplitude of an event was defined as the mean of the peak-to-peak amplitude of the waves in a train of pulsations,
measured in chart lines. The use of the calibration curves, (chapter 4) converted the amplitudes to gammas. The advantage of expressing the magnetometer sensitivity in gammas per chart line (c.f. chapter 4) is very obvious. Since the magnetometers measure the time rate of change of the magnetic field, clearly amplitudes will be affected by the level of magnetic activity. For pulsations superimposed on longer period variations, the errors involved depended on the amplitudes of these long period events. Days in which observatory records showed large irregular fluctuations were termed "disturbed days" and induction magnetometer records on such days were not analyzed. The number of such days was few and there was a tendency for pulsations of short period - 10-25 seconds - to persist for the most part of these days. The magnitude of the error in the determination of the amplitude of an event very much depended upon the amplitude of the event: those events with peak-to-peak amplitudes of two chart lines could have an error as high as 25%. The mean error in the amplitude determination is likely to be about 5% (corresponding to an average amplitude of 10 chart lines)

3. Phase difference

The phase difference between any two components of pulsations varied irregularly along the train and could not
be determined with any confidence. However, those events in which the horizontal components, to within 20°, were nearly in phase or 180° out of phase, along the trace were noted. The phase of the vertical component was often observed to be intermediate between those of the horizontal components.

4. **Time of occurrence**

Though an event could last from a few minutes to a few hours, its time of occurrence was defined as the time when it developed its maximum amplitude in any one of the components. If an event showed equal amplitude at different times along the trace, the mean of the times of occurrence of the maximum amplitudes was taken as the occurrence time. Time determinations have probable errors of less than half a minute.

5. **Most frequently occurring pulsation**

The continuity of an event was defined as its duration in units of two minutes. The maximum continuity an event could have in one hour is thus 30. Within each hour the event which had the highest continuity in any of the three components was defined as the most frequently occurring pulsation. In each hour, more than one event could be taken as the most frequent if the durations differed by less than ten minutes. Since the amplitudes were not taken into account in this definition, the most frequently occurring
event in an hour might have its maximum amplitude and hence its time of occurrence, as defined in 4, outside that hour. There is no ambiguity here because under this heading the interest is in the duration rather than the time of occurrence.

6. Event type

As was described in chapter 1, the most recent of the IAGA notations subdivides both daytime and nighttime pulsations into a number of subgroups according to their periods. This subdivision was not found helpful here because the variation in period along the train of a single event would often place it in two subgroups of the notation. To avoid this, the earlier, broader IAGA notation, classifying events as pc's or pt's is used here. Hence whenever pc appears here its equivalent in the recent notation is pc3 or pc4, and pt here is equivalent to Pi2. Events which exhibited distinct transient decay and of short duration were classified as pt's (Pi2) while those events which showed regular wave shaped without any clear amplitude decay were termed pc's (Pc3 or Pc4). Because pt's showed a great amount of irregularity in wave shape their amplitude determination was difficult and consequently few of the pt's which occurred were really scaled.

The parameters measured here were not intended to bring out all the general characteristics of micropulsations in
S.W. England. They were thought, however, sufficient for the project, namely to examine the vector property of the pulsations and their variation with time of the day and with distance from the sea coast.

It should be borne in mind that because of their high degree of variability, long term average features of micropulsation activity are more important than short term characteristics. In the description given below only long term average features are emphasized; the short term averages are only described in a few places to show the degree of variability of the parameters.

Period versus GMT

In order to make a comparison between the results obtained by STUART and USHER (1966) using a total field rubidium magnetometer, and this analysis, the period of the predominant pulsation in each hour was plotted against GMT. The error in each period of an event was ±5 seconds. Where spaces allowed in the plot, an event was plotted as if it occurred at half past the hour of its occurrence. Thus, generally the position of a dot representing the event in the plot within its hour of occurrence was of no significance. All data obtained from the three locations between March 2nd and June 14th, 1966, were used for this plot. Data obtained during single component measurements could not be used for
this plot because of the lack of knowledge of the events in the other components. There was no advantage in plotting this graph for each of the three components of pulsations. The vertical to N-S and vertical to E-W amplitude ratios versus period.

One would expect that any sea-land boundary effect on recorded pulsations would decrease with increasing distance from the coast. Again the magnitude of the effect is expected to depend on the direction of polarization of the magnetic changes relative to the coastline. Thus it was necessary that data from each of the recording sites be treated separately. Distinction had to be made between those pulsations polarized in a N-S plane and those in an E-W plane. Graphs were plotted of the vertical to N-S and vertical to E-W amplitude ratios against the period of pulsations at each location. In the vertical to N-S amplitude ratio plot only those events which had predominantly N-S polarization were selected, while for the vertical to E-W amplitude ratio plots, only events with predominantly E-W polarization were considered. Of course, only the data obtained during the simultaneous recording of all components at each site were used.
The ratio of the calculated vertical component to the observed vertical component versus period.

It was found that the amount of vertical component tended to bear a linear relationship with the horizontal components when the pulsations were polarized either mainly in the E.W direction or in the N-S direction. To investigate whether such a relationship holds when the pulsations had arbitrary polarization, a plot of \( \frac{\text{calculated } Z}{\text{observed } Z} \) against period was made. Unfortunately this plot could only be made with the data obtained at Hartland Point and the Observatory where some events with an appreciable Z component were found to be either in phase or about 180° out of phase. The difficulty in determining the phase difference between the horizontal components excluded most of the events from this plot. Pt's mainly satisfied the requirements.

Occurrence versus the local time

In this plot no account is taken of the amplitude or period of the pulsation nor of the component in which it is polarized. The number of separate events occurring in each hour over a five month period was counted from the data sheet; by adding the daily events for each hour from March to July. The total number of events per hour were then plotted against time of day.
The amplitude ratios of micropulsations observed simultaneously at all sites.

A plot of the vertical to horizontal amplitude ratios against period is useful for direct comparison of observation with theory. The variation of this ratio could be due to a variation of either the vertical component, the horizontal component or both. A plot of the amplitude ratios of pulsations observed simultaneously at the three sites would show which of the components varied. Thus plots were made of the ratios of amplitudes of each of the three components of micropulsations simultaneously observed at the field sites. During the recording of the single components, most of the pulsations which occurred had periods between 30 and 40 seconds. Thus any period effect could not be investigated, and therefore the ratios were plotted against GMT, to obtain a broad spread of points.

The variation of the plane of polarization of pulsations with the time of day.

A visual inspection of some day’s records suggested that the distribution of amplitudes between the horizontal components of pulsations was not constant throughout the day, as was also suggested by the analysis in chapter 3. Graphs of the amplitude ratios of the E-W to N-S components of micropulsations observed at each of the three recording sites
plotted as a function of GMT were drawn. The phase difference between the horizontal components varied irregularly and it was not easy to take this into consideration in the method of analysis adopted.

The E-W to N-S amplitude ratios versus the period of pulsations.

It is important to know whether the distribution of amplitudes between the two horizontal components of pulsations depends on the period of the variations or on the time of their occurrence. The dependence of this parameter on event type could be very important. Graphs were therefore made of the E-W to N-S amplitude ratios against periods of the events. Account was also taken of their time of occurrence and, where it was found helpful in interpretation, event types were identified.

The errors of measurement.

As has been pointed out, the period attributed to an event could be in error by as much as ±5 seconds. Errors involved in amplitude determination depended on the period and amplitude of the event and on the level of magnetic activity. Since the noise level was of the order of half a chart line in amplitude, those events whose amplitudes were only two or three lines thus had a higher probable error than those events with larger amplitudes. Now, amplitude determinations were made by counting the number of chart
lines occupied by the peak-to-peak wave traces. Thus events which occurred under magnetically quiet conditions were less distorted and thus were expected to have smaller errors.

To find to what extent the level of magnetic activity affected the measured amplitudes of events, a selected portion of a record was firstly scaled manually and the average amplitude of the events determined. Secondly, the average amplitude was then evaluated by a computer technique and the two results were compared. The use of a computer allowed the removal of long period oscillations which were expected to affect the manually scaled amplitudes of the events. The numerical method of filtering the record was that due to BLACKMAN and TUKEY (1958). 20 minutes length of record centred on 13.00 hours of the 12th March, 1966, was digitized at time intervals, \( \Delta t \), equal to five seconds, thus giving 240 observation points. For each observed point a weighted running mean centred on that value was subtracted. Thus from the original data \( -u_1, u_2, \ldots, u_n - \), a new series of weighted data \( -u'_1, u'_2, \ldots, u'_{n-2m} - \) was obtained. \( N \) was the total number of data points (240 in this case) and \( m \) was an integer which determined the cut off frequency of the filter, its value here was 12. The relation between the old and new series is given by

\[
 u'_i = u_{i+m} - \sum_{j=-m}^{m} W_j u_{i+m+j}, \quad i=1, 2, \ldots, n-2m. 
\]
A very effective high pass filter results if

\[ W_j = \frac{1}{2m} \left( 1 + \cos \frac{n_j}{m} \right). \]

The cut off frequency of the filter is given by \( 1/m x \Delta t \); thus the longest period passed by the filter used was \( 12 \times 5 = 60 \) seconds. The response, \( R \), of the filter is given by

\[ R = \left( 1 - Q(f) \right)^2 \]

where

\[ Q(f) = Q_0(f) + \frac{1}{2} Q_0(f+f') + \frac{1}{2} Q_0(f-f') \]

and

\[ Q_0(f) = \sin \frac{nf}{f_p} f' = 1/2m \Delta t. \]

Fig. 6.1 is the frequency of the high pass filter. Though the response is not linear, it is to be noted that for frequencies above the cut off frequency, the deviation of the response from unity is not greater than 3\%. However, for frequencies below the cut off frequency the attenuation is considerable. Another point to note is that the number of data points was reduced by 2m by the filtering process. The filtering was programmed to Imperial College IBM 7090/1401 computer. The filtered pulsations were drawn on a fresh chart paper and peak-to-peak amplitude measurements were then made. It was observed that the filtered amplitudes could differ from the corresponding unfiltered amplitudes by
FIG. 6.1. RESPONSE OF HIGH-PASS FILTER.
as much as 5%. However, the average of the two differed by less than 2%. Since the amplitude of the pulsations from one cycle to another could vary over wider limits, it was therefore thought that the effect of superposition of long period events on the pulsations considered in this study introduced a negligible error on the measured amplitudes of the pulsations. This is understandable when it is remembered that the magnetometer was less sensitive to long period pulsations.

There were occasions when pulsations observed in one component were absent in another component. To evaluate the amplitude ratio between the components of pulsations in these circumstances, it was necessary to assign a minimum value to the amplitude of pulsation in the component in which it was not observed in order to avoid infinite values for the ratios. Thus in some of the graphs to be described below such as the $|Y/X|$ plots, no significance should be attached to the absolute maximum values of the ratios. Because of this and the variation in pulsation activity from day to day, only general trends are important.

6.3 Description of the Results.

1. Occurrence versus time of day.

Fig. 6.2 is a plot of micropulsation activity against time of day. No account was taken of the type, period or
FIG. 6.2. MICROPULSATION ACTIVITY IN S.W. ENGLAND VERSUS TIME OF DAY.

polarization of events. Generally activity is high between 06.00 hours and 13.00 hours, with a broad peak around noon. Thus the probabilities of pulsations occurring in each hour between 06.00 and 13.00 hours are only marginally different. Another peak in activity occurs around 21.00 hours. Minimum activity occurs about 19.00 and 00.00 hours. The times of occurrence of the peak activities correspond to the times when either pc's or pt's are very frequent. Identifying the morning and noon peak activity as pc activity and the night peak as pt activity it is to be noted that pt's are more selective in their time of occurrence than pc's; pc's show broad activity between 06.00 and 13.00 hours, while pt's have a relatively sharp peak between 21.00 and 22.00 hours.

2. Period of the predominant pulsation versus time of day.

Fig. 6.3 is a plot of the period of the predominant pulsation versus time of day. As has been explained earlier, the predominant event in each hour is the event which has the highest continuity in that hour. In this plot, no distinction is made between pc's and pt's, but most of the events which occur between 18.00 and 04.00 hours are certainly pt's. Starting from midnight the period of the predominant pulsation decreases from about 80 seconds to
FIG. 6.3. VARIATION OF THE PERIOD OF THE PREDOMINANT PULSATION WITH TIME OF THE DAY.

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about 40 seconds by 04.00 hours, reaching a minimum of just over 30 seconds between 08.00 and 11.00 hours. After 11.00 hours the period starts to increase, though slowly until about 18.00 hours when its average value is around 50 seconds. A rapid period increase occurs after 18.00 hours reaching a maximum average value of over 100 seconds between 21.00 and 22.00 hours.

Though the details of the shape of this curve may not be ascertained from only five months data, the general trend is obvious. The form of the variation of the period during day time is seen to be different from that at night. Nightime period variation is characterized by relatively rapid changes; the rate of increase of the period is positive between 16.00 and 22.00 hours but between 23.00 and 04.00 hours it is negative. Day time period variations are characterized by relatively small changes. Between 06.00 and 11.00 hours the period of the predominant event is generally under 40 seconds, with an average value of about 33 seconds. However, between 12.00 and 17.00 hours, the average period of the predominant event is about 40 seconds. The greatest change in the period of predominant pc event occurs between 11.00 and 12.00 hours. This general trend is obvious from an examination of a few days' micropulsation records. If a distinction is made between pt's and pc's and if the daylight hours are
taken to be from 06.00 to 18.00 hours then from Fig. 6.3 the following deductions are obvious:-

a. The period of the predominant pt depends strongly on the time of the day.

b. During the morning hours the period of the predominant pc event is about 34 seconds. At noon and during the afternoon the period of the predominant pc shifts to about 41 seconds.

c. An examination of Figs. 6.2 and 6.3 reveals the contrasting characteristics of pt's and pc's: pt's are night time phenomena with periods longest at their time of maximum activity; pc's are mainly daytime pulsations with their periods shortest around the time of maximum activity.

3. The E-W to N-S amplitude ratios \( (Y/X) \) versus time of day.

Figs. 6.4 to 6.6 are plots of the E-W to N-S amplitude ratio versus time of day at each of the three stations - Hartland Point, Royal Greenwich Observatory Hartland and Shetbear. The observation dates at the stations were different. While geographic bearings were used at the Observatory, magnetic bearings were used at Hartland Point and Shetbear. In each plot, the best curve through the points was fitted by eye.
FIG. 6.4. RATIO OF THE MAGNETIC EAST-WEST COMPONENT (Y) TO THE MAGNETIC NORTH-SOUTH COMPONENT (X) FOR MICROPULSATIONS OBSERVED AT HARTLAND POINT VERSUS G.M.T.

April 2nd - 30th, 1966
FIG. 6.5. RATIO OF THE GEOGRAPHIC EAST-WEST COMPONENT (Y) TO THE GEOGRAPHIC NORTH-SOUTH COMPONENT (X) FOR MICROPULSATIONS OBSERVED AT THE OBSERVATORY HARTLAND, AS A FUNCTION OF G.M.T.

March 2nd - March 24th, 1966
FIG. 6.6. RATIOS OF THE MAGNETIC EAST-WEST COMPONENT (Y) TO THE MAGNETIC NORTH-SOUTH COMPONENT (X) FOR MICROPULSATIONS OBSERVED AT SHEBBEAR AS A FUNCTION OF G.M.T.
From midnight, the average value of the ratio in Fig. 6.4 increases from approximately unity, reaching a maximum in the morning hours at about 08.00 GMT. A minimum value of the ratio occurs at noon after which it increases and approaches unity about 21.00 hours. Between 10.00 and 12.00 hours, there is a rather rapid change in the value of the ratio from being much greater than unity to much smaller. The above trend appears in Figs. 6.5 and 6.6, though there are some differences in the shape of the "average value" curve. Differences in the curve shapes at the three stations may arise from any or a combination of the following reasons:

a. The number of observations is small, particularly at Shebbar.

b. The axes of reference are different: the declination at the Royal Greenwich Observatory Hartland, is about 9°25'W.

c. There may be a seasonal variation of the shape of the curve.

d. The vector property of pulsations may be altered by the local geology (c.f. chapter 2).

Now, by identifying event types by their time of occurrence it is to be noted that for pt's the distribution of amplitudes between the two horizontal components is about equal. However, for pc's the distribution of amplitude
between the two orthogonal horizontal components is a function of time of day. During the late morning hours there is a strong tendency for the pulsations to have bigger amplitudes in the E-W plane than in the N-S plane; the reverse is true during the afternoon. At the Royal Greenwich Observatory, Hartland, as well as at Hartland Point, where large numbers of data points were obtained, the time of occurrence of the maximum amplitude in the E-W plane is around 08.00 hours; the maximum amplitude in the N-S plane occurs about 13.00 hours. This trend of events is obvious from a mere examination of a number of records, particularly records on days when there were many hours of continuous activity. However, on some days, this trend is not apparent and the reverse may be suggested occasionally. On the 8th April, 1966, many hours of pulsation activity were recorded at Hartland Point. The mean amplitudes in each of the horizontal components in each hour was determined. The hourly means of the E-W to N-S amplitude ratios have been plotted against time of day in Fig. 6.7. The shape of the curve is similar to that of Fig. 6.4, confirming that the general trend described above is at times observable from a single day's results.

Like other micropulsation parameters the ratio, \(|Y/X|\), shows a high degree of variability over short time intervals. This is illustrated in Fig. 6.8 which shows the variation of
FIG. 6.8. VARIATION OF EAST-WEST TO NORTH-SOUTH PEAK-TO-PEAK AMPLITUDE RATIO (\( \frac{X}{Y} \)) OF MICROPULSATION ACTIVITY ALONG TRAINS OF PULSATIONS.
'Y/X' along trains of pulsations. Along selected trains, the ratio was evaluated at half cycle intervals. The times marked on each curve are when the train of pulsation started and when it ended. The data was obtained from the record taken at Hartland Point on the 16th April, 1966. Data for the curves (A) and (B) were taken from pulsation trains which occurred in the morning. Though the ratio varies between half cycles, its mean for each of the two curves is greater than unity, again indicating a bigger average amplitude in the E-W component than in the N-S component. Data for curve (C) was taken from an afternoon train of pulsations. Though there is a large variation between half cycles, the average value of the |Y/X| ratio along the train is considerably less than unity, and clearly has an average value less than those of (A) and (B), in general agreement with the trend predicted by Fig. 6.4. These results strongly suggest that the plane of polarization of micropulsations in S.W. England varies with the time of day.

4. The E-W to N-S amplitude, |(Y/X)|, versus period of pulsations.

It was noted in section 6.3.2 that the period of the predominant event varies with the time of day. In particular a rapid change in period of the daytime event was observed to occur between 09.00 and 12.00 hours. In the last section
it was concluded that the plane of polarization of micro-pulsations varies with the time of day. The rate of change of the plane of polarization is greatest between 09.00 and 12.00 hours. These results may be interpreted in one of two ways:

(i) In the period range covered by this study, pc's are divisible into two groups. One group which occurs in the morning hours with an average period of about 33 seconds has mainly an E-W polarization. The other group with a longer average period of about 41 seconds occurs most frequently in the afternoon and has predominantly a N-S polarization. This implies that the change in the plane of polarization is a period effect.

(ii) The period of micropulsations varies with the time of day, being longer in the afternoon than in the morning. The vector representing the micropulsation field in a horizontal plane precesses such that it is directed close to E-W direction in the mornings and close to the N-S direction in the afternoon. This implies that the changes in the plane of polarization are time dependent.

Thus it is not known whether the variation of the plane of polarization of pulsations is a period or a time effect. In an attempt to examine the controlling factor Figs. 6.9 to 6.11 have been drawn. These are ratios of the E-W amplitudes
Hartland Point, April 2nd - 30th, 1966

○ - events which occur between 05-12 G.M.T.
• - events which occur outside the interval 05-12 G.M.T.

x - pts whose periods lie in pc period range

FIG. 6.9. RATIO OF THE MAGNETIC EAST-WEST COMPONENT (Y) TO MAGNETIC NORTH-SOUTH COMPONENT (X) OF MICROPULSATIONS VERSUS PERIOD.
FIG. 6.10. RATIO OF THE GEOGRAPHIC EAST-WEST COMPONENT (Y) TO GEOGRAPHIC NORTH-SOUTH COMPONENT (X) OF MICROPULSATIONS VERSUS PERIOD.

Observatory, March 2nd - 28th, 1966

- events which occur between 06-11 G.M.T.
- x pts whose periods lie in pc period range
- events which occur outside the interval 06-11 G.M.T.
Shebbear, May 2nd. - June 13th. 1966

- events which occur between 04-10 G.M.T.
- pts whose periods lie in pc period range.
- events which occur outside the interval 04-10 G.M.T.

FIG. 6.11. RATIOS OF THE MAGNETIC EAST-WEST COMPONENT (Y) TO MAGNETIC NORTH-SOUTH COMPONENT (X) OF MICROPULSATIONS VERSUS PERIOD.
(Y) to N-S amplitudes (X) of micropulsations at each of the three stations, plotted as a function of period. In each case circles represent events which occurred at times when the corresponding E-W to N-S amplitude ratio \(|Y/X|\) versus time of day plot (Figs. 6.4 - 6.6) showed a relatively high value for the ratio. The crosses stand for pt events whose periods are under 60 seconds. Dots represent all other events and are mainly those which occurred in the afternoon and night. It was thought that an examination of the distribution of both the dots and circles would give an indication of any time or period effect on the ratio. Any period effect is difficult to detect because the period of pc's in S.W. England shows a small range of variation - 20-50 seconds. In Fig. 6.9 the few dots appearing at periods less than 35 seconds have relatively higher \(|Y/X|\) ratio than those appearing at periods greater than 35 seconds. There is also a tendency for the circles in the short period ranges to have higher \(|Y/X|\) ratios. In Fig. 6.10, the dots in the short period range (less than 35 seconds) tend to have bigger \(|Y/X|\) ratios than those in the long period range (greater than 35 seconds) if only events with periods less than 60 seconds (pc's) are considered. These, very marginally suggest a period effect. But there appears to be no particular trend in the distribution of circles in Fig. 6.10. In Fig. 6.11 there appears to be
an equal probability of dots appearing at both short and long periods. The latter observation seems to suggest a time effect. It may be that both time and period effects are present. A large amount of data is needed to resolve this problem.

Whatever the controlling factor may be, the graphs of Figs. 6.4 to 6.8 strongly suggest that the plane of polarization of micropulsations in S.W. England undergoes a diurnal variation. An examination of the slopes of curves in Figs. 6.4 to 6.7 suggests that the rate of change of this plane of polarization is not constant: it is greater before noon and smallest in the afternoon.

5. The amplitude ratios of the X component of micropulsations observed simultaneously at the three sites.

Figs. 6.12 to 6.14 show the amplitude ratios of the magnetic N-S component (X) of micropulsations observed simultaneously at any two of the recording sites - Hartland Point (HP), Royal Greenwich Observatory, Hartland (OB) and Shebbear (SH) plotted as a function of GMT. The plot against GMT was dictated by the fact that the pulsations which occurred had only a small range of period (30-40 seconds) and by the results of the last section which show a diurnal trend in the polarization of pulsations. Though there is a considerable scatter in Fig. 6.12 the mean value of the ratio
FIG. 6.12. AMPLITUDE RATIOS OF THE MAGNETIC NORTH-SOUTH COMPONENT (X) OF MICROPULSATIONS OBSERVED SIMULTANEOUSLY AT HARTLAND POINT (HP) AND THE OBSERVATORY HARTLAND (OB) VERSUS G.M.T.
FIG. 6.13. AMPLITUDE RATIOS OF THE MAGNETIC NORTH-SOUTH COMPONENT (X) OF MICROPULSATIONS OBSERVED SIMULTANEOUSLY AT HARTLAND POINT (HP) AND SHEBBEAR (SH) VERSUS G.M.T.
FIG. 6.14. AMPLITUDE RATIOS OF THE MAGNETIC NORTH-SOUTH COMPONENT (X) OF MICROPULSATION OBSERVED SIMULTANEOUSLY AT THE OBSERVATORY HARTLAND (OB) AND SHEBBEAR (SH) VERSUS G.M.T.
between the amplitudes of the N-S components of pulsations at Hartland Point and the Observatory is close to unity. In Figs. 6.13 and 6.14, the weighted mean (dotted line) of each set of data is clearly less than unity. In each figure the points seem to fall into two groups: the first group of points corresponding to late morning events have an average ratio less than 0.8; while the second group corresponding to afternoon events have a mean value greater than 0.8 but definitely less than unity. The change over from one average value to the other appears to occur about 11.00. The reality of this effect is difficult to assess from Fig. 6.13 because of the small amount of data, but Fig. 6.14 appears more convincing. It may be important to remark that this change over from one average value of the ratio to another occurs at about the time when the period of pc events have been observed to change relatively rapidly and also the time when the rate of change of the plane of polarization is noted to be greatest.

6. The amplitude ratios of the $Y'$ component of micropulsations observed simultaneously at the three sites

Fig. 6.15 and 6.16 are the amplitude ratios of the magnetic E-W component ($Y'$) of micropulsations observed simultaneously at any two of the stations plotted as a function of GMT. The dotted line represents the weighted
Fig. 6.15. Amplitude ratios of the magnetic east-west component (y) of micropulsations observed simultaneously at Hartland Point (HP) and Shebbeare (SH) versus G.M.T.
FIG. 6.16. AMPLITUDE RATIOS OF THE MAGNETIC EAST-WEST (Y) COMPONENT OF MICROPULSATIONS OBSERVED SIMULTANEOUSLY AT HARTLAND POINT (HP) AND ROYAL GREENWICH OBSERVATORY HARTLAND (OB) VERSUS G.M.T.
average of the ratio. The subscripts in these figures have meanings similar to those in the last section and for the same reason as in the last section, GMT was chosen as the independent variable. The two figures indicate that the amplitudes of the E-W component of simultaneous pulsations are equal at all the three sites.

7. The amplitude ratios of the Z component of micropulsations observed simultaneously at the three sites.

Figs. 6.17 to 6.19 are plots of the amplitude ratios of the vertical component (Z) of micropulsations observed simultaneously at any two of the stations against period. The subscripts in each of the figures have meanings similar to those of the last section. In Fig. 6.17 there is a clear indication that the amplitude ratio for events observed simultaneously at Hartland Point and Shebbear increases with decreasing period, though the small number and scatter of observations at periods greater than 60 seconds make the dependence of the ratio on frequency difficult to assess at such periods. The dotted line represents the weighted mean of the ratio. A very similar trend is obvious from Figs. 6.18 and 6.19. It is interesting to note the similarity in the shape of the curves. To a very rough approximation, the height of the curves in Figs. 6.18 and 6.19 are equal at corresponding periods. This suggests that the total change
Fig. 6.17. Amplitude ratios of the vertical component (Z) of micropulsations observed simultaneously at Hartland Point (HP) and Shebbear (SH) versus period.
FIG. 6.18. AMPLITUDE RATIOS OF THE VERTICAL COMPONENT (Z) OF MICROPULSATIONS OBSERVED SIMULTANEOUSLY AT HARTLAND POINT (HP) AND THE OBSERVATORY (OB) VERSUS PERIOD.
FIG. 6.19. AMPLITUDE RATIOS OF THE VERTICAL COMPONENT (Z) OF MICROPULSATIONS OBSERVED SIMULTANEOUSLY AT THE OBSERVATORY (OB) AND SHEBBEAR (SH) VERSUS PERIOD.
of the vertical field between Hartland Point and the Observatory only two miles away from it is approximately equal to that between the Observatory and Shebbear which is about 15 miles away. On the basis of the distances between the sites it is suggested that the source of the enhancement of \( Z \) has a stronger effect between Hartland Point and the Observatory than between the Observatory and Shebbear.

Fig. 6.20 shows the amplitude ratios of the vertical component of pulsations observed simultaneously at Hartland Point (HP) and Shebbear (SH) plotted as a function of GMT. The two stations were chosen for this plot because it is between them that there occurs the greatest difference between the amplitudes of simultaneous events. The scatter does not suggest any particular trend.

8. **The vertical to magnetic E-W amplitude ratio (Z/Y) of micropulsations versus period.**

Figs. 6.21 to 6.23 are plots of the vertical to magnetic E-W amplitude ratio (Z/Y) of micropulsational activity against period at each of the stations. Circles represent events for which \( |Y/X| \geq 2 \), while dots stand for events for which \( 1 \leq Y/X < 2 \), in Figs. 6.21 and 6.22. The dotted line represents the weighted mean. The events used for the plot of Fig. 6.23 were such that \( |Y/X| \geq 0.9 \). The use of different criteria for this latter plot was due to the fact that
FIG. 6.20. AMPLITUDE RATIOS OF THE VERTICAL COMPONENT (Z) OF MICROPULSATIONS OBSERVED SIMULTANEOUSLY AT HARTLAND POINT (HP) AND SHEBBEAR (SH) VERSUS G.M.T.
FIG. 6.21. VERTICAL TO MAGNETIC EAST-WEST AMPLITUDE RATIO \( \left( \frac{Z}{Y} \right) \) OF MICROPULSATION ACTIVITY AT HARTLAND POINT Versus Period.
FIG. 6.22. VERTICAL TO GEOGRAPHIC EAST-WEST AMPLITUDE RATIO \( \left( \frac{Z}{Y} \right) \) OF MICROPULSATION ACTIVITY AT THE OBSERVATORY VERSUS PERIOD.
FIG. 6.23. VERTICAL TO MAGNETIC EAST-WEST AMPLITUDE RATIO $\left(\frac{Z}{Y}\right)$ OF MICROPULSATION ACTIVITY AT SHEBBEAR VERSUS PERIOD.
relatively few events at Shebbear were such that $|Y/X| > 1$. The main aim in these plots was to compare theory with observation. An attempt can thus be made to look for a relation between the vertical and horizontal components of pulsations where these are polarized in an E-W plane. It is clear from Fig. 6.21 that the average value of the ratio is close to 0.5 at Hartland for signals in the period range 20-50 seconds. Any dependence of this ratio on period is not resolved because of the scatter. Some of the scatter is obviously due to the non-zero value of pulsation amplitudes in the meridian plane. It will be observed from Fig. 6.22 that the average value of the ratio $|Z/Y|$ at the Observatory is about 0.35 in the period range 20-50 seconds. Again the presence of considerable scatter makes the resolution of period dependence difficult. At Shebbear, it is observed from Fig. 6.23 that the average value of the ratio is less than 0.1. The paucity of data points does not warrant a more accurate estimate of this ratio. However, it is significant to note that the vertical to magnetic E-W amplitude ratio of pulsations decreases progressively from about 0.5 at Hartland Point to under 0.1 at Shebbear for events whose period lie between 30 and 50 seconds.
9. The vertical to magnetic N-S amplitude ratio \((Z/X)\) of micropulsations versus period.

Plots of the vertical to magnetic N-S amplitude ratio, \(|Z/X|\), of micropulsational activity at each of the locations against period are shown in Figs. 6.24 to 6.26. An attempt was made to select those events with predominantly meridian polarization. In Figs. 6.24 and 6.25, circles represent events with \(|Y/X| < 0.3\) while dots stand for events for which \(0.75 > |Y/X| > 0.3\). In Fig. 6.25, however, only those events for which \(|Y/X| < 0.67\) were used for the plot. As in the plots of the last section the scatter is considerable at each station. This makes it difficult to assess the dependence of the ratio on the period of pulsations. The average value of the ratio for pulsations with period between 30 and 50 seconds is 0.35 at Hartland Point, 0.30 at the Observatory and about 0.15 at Shebbear. Again the evidence suggests that the vertical to horizontal amplitude ratio of micropulsations polarized in the meridian plane decreases progressively from a value of 0.35 at Hartland Point to about 0.15 at Shebbear.

As with other parameters of micropulsational activities the amplitude ratio of the vertical to the horizontal components may be expected to show a high degree of variability.
FIG. 6.24. VERTICAL TO MAGNETIC NORTH-SOUTH AMPLITUDE RATIO \( \frac{Z}{X} \) OF MICROPULSATION ACTIVITY AT HARTLAND POINT VERSUS PERIOD.
FIG. 6.25. VERTICAL TO GEOGRAPHIC NORTH-SOUTH AMPLITUDE RATIO \( \frac{Z}{X} \) OF MICROPULSATION ACTIVITY AT THE OBSERVATORY VERSUS PERIOD.
FIG. 6.26. VERTICAL TO MAGNETIC NORTH-SOUTH AMPLITUDE RATIO $\left( \frac{z}{x} \right)$ OF MICROPULSATION ACTIVITY AT SHEBBEAR VERSUS PERIOD.
IG.B.27. VARIATION OF, A, VERTICAL TO EAST-WEST PEAK-TO-PEAK AMPLITUDE RATIO \( \frac{A}{V} \), B, VERTICAL TO NORTH-SOUTH PEAK-TO-PEAK AMPLITUDE RATIO \( \frac{B}{V} \) OF MICROFUSATION ACTIVITY ALONG TRAINS OF PULSIONS.

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E-W peak-to-peak amplitude ratio, $|Z/Y|$, curve (B), the vertical to N-S peak-to-peak amplitude ratio $|(Z/X)|$ of micropulsational activity along trains of pulsation. These ratios were evaluated at half cycle intervals. The time of occurrence of the pulsations are marked on the curves. The record was taken at Hartland Point. Pulsations in (A) had mainly an E-W polarization while in (B) the polarization was mainly N-S. It is observed that the ratios vary from half cycle to half cycle along the train of pulsations. A large number of curves similar to Fig. 6.27 which are not reproduced here were drawn. The mean of the ratio varied from one train of pulsations to another even if the periods of the pulsations in the trains were equal. This variation of the ratios from one train to another of the same pulsation may be responsible for the considerable scatter in the plots described above.

10. The ratio of the calculated to the observed amplitude of the vertical component of pulsations versus period.

An inspection of records and the results of the last two sub-sections suggested that to a rough approximation, there is a linear relationship between the amplitude of the vertical component and the amplitude of the horizontal components when the latter are polarized either mainly in an
E-W plane or mainly in a N-S plane. This seemed to suggest that $Z$ could be expressed as

$$Z = \alpha \bar{X} + \beta \bar{Y}$$

when there is simultaneously appreciable amplitude present in the two horizontal components. $\alpha$ and $\beta$ are independent of the magnitudes of $\bar{X}$ and $\bar{Y}$ and their values vary from one station to another. The positive $X$ is towards North; positive $Y$ is towards East; and positive $Z$ is vertically downwards. Values of the constants for each location used for calculating $Z$ are those obtained in sub-sections 6.3.8 and 6.3.9 and are as follows:

- Hartland Point, $\alpha = 0.35$, $\beta = 0.50$
- Observatory $\alpha = 0.30$, $\beta = 0.35$

Data from Shebtear was not used because of the small values of $Z$ there. Because the data suggested that $\alpha$ and $\beta$ were phase dependent the calculations were mainly performed for those events in which the two horizontal components were, to within $20^\circ$, either in phase or $180^\circ$ out of phase. As was mentioned earlier, it was mainly pt's that satisfied this condition. Fig. 6.28 (a) is a plot of the ratio of the calculated amplitude, using equation (2), to the observed amplitude. A histogram showing the spread of the ratio is shown in Fig. 6.28 (b) and was taken from (a). The scatter is considerable though not unexpected. The high probability
FIG. 6.28. (a). RATIO OF CALCULATED TO OBSERVED AMPLITUDE OF VERTICAL COMPONENT OF MICROPULSATIONS IN S.W. ENGLAND AGAINST PERIOD.

(b). HISTOGRAM OF THE NUMBER OF POINTS AGAINST RANGE OF \( \frac{Z_{\text{calculated}}}{Z_{\text{observed}}} \)
(TAKEN FROM (a)).
for the ratio lying between 0.9 and 1.2 may perhaps be significant. The mean value is about 1.1. Though these plots are not as convincing as the inspection of those records in which there is zero phase difference between the horizontal components, the closeness of the mean of the ratio to unity seems to suggest that to a very rough approximation a linear relation exists between the amplitude of the vertical components and the associated horizontal components when the latter have a negligible phase difference between them.

6.4 Discussion

The most striking difference in the vector characteristic of micropulsations at the three British Observatories is the amount of the vertical field present. The biggest amplitude in this component occurs at Lerwick where \(|Z/X|\) is of the order of 7/10. At Hartland \(|Z/X|\) is about 3/10 while the ratio is generally less than 1/10 at Eskdalemuir. The analysis, in this chapter, of the vertical component of pulsations occurring at Hartland and its surroundings has revealed the following properties:

(i) The amplitude of the vertical component decreases with distance from the coast.

(ii) The ratio of the vertical to the associated
horizontal component depends on the direction of polarization of the pulsations in a horizontal plane.

(iii) The rate of decrease of the vertical component amplitude decreases with distance from the coast. That these are qualitatively what should be expected if the observed vertical component were caused by the sharp conductivity contrast at the sea coast is obvious from Fig. 2.5 of chapter 2. Unfortunately, no quantitative comparison between theory and observation can be made because of the following factors:

a. The effect of the poorly conducting sea bottom will certainly be an important factor so that the mathematical model involving an infinite deep ocean is inappropriate.

b. As will be discussed later, the plane wave approximation for micropulsations is doubtful.

c. The idealized straight coastal boundary in the theory does not hold in S.W. England, (c.f. Fig. 5.1). All the plots of the vertical to horizontal amplitude ratios, (Figs. 6.21 to 6.26), showed considerable scatter which could not allow the resolution of the dependence of the ratio on period. At each station the best curve for the mean was a straight line parallel to the period axis. This implies that the
ratios are independent of period. However, theory predicts period dependence, as shown in Fig. 2.5. There is no conflict between theory and observation when it is remembered that most of the events analyzed had their periods between 30 and 40 seconds. As will be easily deduced from Fig. 2.5, the expected difference between the ratio for events of 30 seconds and 40 seconds is about 0.08. This is much less than the scatter in the plots. Thus observations and theory in this instance remain unresolved.

It is not suggested that the observed vertical component of pulsations is entirely due to the sea effect. All that is implied here is that the greater part of it arises from this cause. The fraction of the vertical field due to other causes may be estimated as follows: If equation (2) of section 3 is taken to be strictly correct for the part of the vertical component due to the sea effect, then the scatter in Fig. 6.28(a) may be explained as not only arising from the neglect of phase differences between the horizontal components but also from an intrinsic component $Z_0$ which is introduced because of the existence of finite ratios $|Z/X|$ and $|Z/Y|$ at great distances from the sea. Denoting the part of the vertical component due to sea effect by $Z_S$ then the total vertical field will be $Z = Z_0 + Z_S$. The ratios plotted
in Fig. 6.28 are then $|Zs/(Zo + Zs)|$. Now it has been observed that this ratio is likely to lie between $8/10$ and $13/10$ for stations between Hartland Point and the Observatory. Thus

$$\frac{13}{10} > \left| \frac{Zs}{Zo + Zs} \right| > \frac{8}{10}$$

which can be shown to be consistent with the condition

$$\left| \frac{Zo}{Zo + Zs} \right| < \frac{1}{2} \quad \text{(Appendix r).}$$

Thus the ratio of $Zo$ to the total observed vertical component of the field ($zo + Zs$) consistent with the scatter diagram of Fig. 6.28 is less than $1/5$.

Now at the Observatory it has been noted that

$$\left| \frac{Zs + Zo}{X} \right| \simeq \left| \frac{Zs + Zo}{Y} \right| \simeq \frac{3}{10}$$

therefore

$$\left| \frac{Zo}{X} \right| \sim \left| \frac{Zo}{Y} \right| \sim \left| \frac{Zo}{Zs + Zo} \right| \cdot \left| \frac{Zs + Zo}{X} \right| < \frac{1}{5} \cdot \frac{3}{10}$$

i.e. \( \left| \frac{Zo}{X} \right| < 0.06 \).

This means that in the absence of the sea effect the expected amplitude ratio of the vertical to the horizontal components of pulsations will be less than 0.06. This is not very much different from the value of 0.1 observed at Shebbear. The order of magnitude of the intrinsic vertical component of pulsations deduced here is consistent with the observation at Eskdalemuir Observatory located at about 50 miles from the
sea. Here it was noted that the ratio of the vertical to horizontal component was less than 0.1. The approximate equality of the ratios at Shetbear and Eskdalemuir is consistent with the existence of an intrinsic vertical component $Z_0$. The near equality of the calculated $Z_0$ and the observed value at places distant from the sea supports the deduction that the vertical field due to sea effect may be expressed as

$$Z_s = \alpha \bar{X} + \beta \bar{Y} \quad (2)$$

The total vertical component of pulsations at Hartland may then be expressed as

$$\bar{Z} = \bar{Z}_0 + \bar{Z}_s = \bar{Z}_0 + \alpha \bar{X} + \beta \bar{Y} \quad (3)$$

Equation (3) is an equation of a plane.

The conclusion that the vertical component $Z$ of pulsations at Hartland may be approximated by that given in equation (3) implies that:

(i) The in phase and anti-phase components of pulsations tend to be confined in fixed inclined plane.

(ii) A horizontal direction exists in which the vertical component is vanishingly small, (only $Z_0$ present), when the horizontal vector is along it. PARKINSON (1959, 1962a, 1962b) has observed that at many coastal stations the disturbing magnetic vector tends to be in a fixed plane when the half period is between 5 and 60 minutes. It was explained that the effect could occur because
induced currents are stronger on the seaward side of a coastline either because of the relatively high conductivity of the sea water or because conductivity in the mantle may be higher below oceans than below continents. It is likely that at micropulsation frequencies the influence of a conducting mantle at a depth of some hundred kilometres is negligible. Thus the observed effect here is very likely due only to the sea effect and suggests that the sea effect is at least a contributory cause of the phenomenon studied by PARKINSON.

In chapter 2 it was concluded that if micropulsations were due to a very distant source or current sheet of very large dimensions, the field would be characterized by the absence of the vertical component. The existence of an intrinsic vertical component of pulsations at places near and remote from the sea coast, deduced in this analysis, casts doubts on the plane wave approximation for micropulsation phenomena.

If it be assumed that the intrinsic vertical field is the same at all stations in the United Kingdom the above results can satisfactorily explain how the energy differences between micropulsations observed at the British Observatories and reported by STUART and USHER (1966) arise. Assuming a unit amplitude for the horizontal component of pulsations,
the total field change $\Delta F$ seen by a rubidium magnetometer will be

$$\Delta F = 0.34 \pm (0.06 \times 0.94), \quad (\text{c.f. section 6.1})$$

$$\simeq 0.34 \pm 0.06.$$ 

At Eskdalemuir, where the sea effect is negligible, the above value is the value of the recorded field change. However, at Lerwick and Hartland because of the sea effect the recorded field changes will be respectively

$$\Delta F = (0.34 \pm 0.06) \pm \left( \frac{7}{10} \times 0.94 \right)$$  \hspace{1cm} (Lerwick) \\
$$\Delta F = (0.34 \pm 0.06) \pm \left( \frac{3}{10} \times 0.94 \right)$$  \hspace{1cm} (Hartland) \\

Since the pulsation energy is proportional to the square of the amplitude, it will be clear that the energy ratio between Hartland and Eskdalemuir will be between 0 and $\frac{1}{4}$, while the ratio of the energy of the pulsations at Lerwick to that at Eskdalemuir could be as high as 10. In each case the value of the ratio will depend on the direction of the total field change. Because of the different directions of field changes, much scatter may be expected in the micropulsation energy plot. This large spread in the energy ratios of pulsations occurring at two stations has been observed by STUART and USHER (1966). Their observation of large energy differences with an average value of 1.5$^*$ for the ratio of energies at

*$^*$This value has been revised to a figure $\geq 1.5$ (Dr. Usher, private communication).
Lerwick and at Eskdalemuir is more in accord with energies which account for the sea effect than without. The above discussion shows that as far as pulsations with periods less than about 120 seconds are concerned, the sea effect satisfactorily explains the pulsation energy differences at the three British Observatories. This means that the ground conductivity anomaly which is supposed to exist at Eskdalemuir has no effect on pulsations whose periods are less than 120 seconds. This conclusion has been confirmed by Sir Edward Bullard (private communication) and those working under him who suggested the existence of the anomaly.

Equation (3) predicts the existence of a direction in which the sea effect is negligible, i.e.

\[ Z_s = \alpha X + \beta Y > 0 \]

i.e. \[ \frac{\gamma}{\beta} = -\frac{Y}{X}. \]

If the horizontal pulsation component is inclined to the N-S direction by \( \theta^0 \) then

\[ \tan \theta = -\frac{Y}{X} = \frac{\alpha}{\beta}. \]

At Hartland Point \( \alpha = 0.35 \) and \( \beta = 0.50 \). Thus

\[ \theta = -\tan^{-1}(0.7) = -35^0. \]

Since the declination at Hartland is about \( 90^0 \text{W} \), this means that the horizontal direction corresponding to the minimum vertical component of pulsation is parallel to the direction \( 14^0\text{W} \) of geographic North. Now at the observatory where the
reference axes for the measurement were geographic N-S and E-W, \( \alpha \approx \beta \approx 0.30 \), i.e. \( \theta = -45^\circ \). Thus the direction of polarization of the horizontal component of pulsations giving the minimum vertical component of pulsations is \( 45^\circ \)W of geographic North. Thus the horizontal directions corresponding to the minimum vertical component of pulsations are the same at Hartland Point and the Observatory. Because of the complex coastline in S.W. England (c.f. Fig. 5.1) it is not easy to correlate this direction with the sea boundary. Experimentally cases in which the vertical component was unusually small compared to the horizontal components were observed. Fig. 6.29a shows this clearly. It is observed that in Fig. 6.29a, \( Z \) is very small inspite of large amplitudes in \( X \) and \( Y \) while in Fig. 6.29b, a more common event, \( |Z/X| \) is close to the average value of 0.3 at the Observatory. The event in Fig. 6.29a occurred about 04.30 GMT while that of Fig. 6.29b occurred about 08.00 GMT on the 21st March, 1966. All the traces have the same sensitivity. The existence of a direction of polarization of the horizontal component of pulsations giving a negligible vertical component, is consistent with the prediction of WEAVER's theory (c.f. chapter 2) which requires the magnitude of the vertical component of pulsations to depend on the direction of polarization of the horizontal micropulsation field in the vicinity of a large conductivity gradient.
Fig. 6.29a. Section of record showing an event with large amplitudes in the horizontal components and small amplitude in the Z-component.
Fig. 6.29b. Section of record showing an event with relatively large amplitude in the Z-component.
The diurnal variation of the pulsation periods has been reported by a number of investigators including HOLMBERG (1953), CHRISTOFFEL and LINFORD (1966). The form of the period variation reported here is generally similar to that observed by the latter investigators near Wellington, New Zealand. However, whereas the minimum period occurred at noon at Wellington, its time of occurrence in S.W. England is about 08.00 hours. Generally long period events occur in the night and very early mornings. The above observation is at variance with the theoretical calculations of the expected form of the variation of periods of pulsations by JACOBS and WATANABE (1962), PRINCE and BOSTICK (1964) and GREIF and GREIFINGER (1965). These authors, from the calculation of the wave transmission coefficient of the ionosphere predicted that the frequency of pulsations will shift to higher values during the night hours.

Pc's and pt's show differences in the form of their period variations. While pc's have their minimum period around their time of peak activity, pt's have their longest periods around their time of peak activity (c.f. Figs. 6.2 and 6.3). Another characteristic difference between pc's and pt's is easily observed from Figs. 6.4 to 6.6. While the plane of polarization of pt's appears fixed, that of pc's varies throughout the day. These differences, and difference
in time of occurrence and wave form seem to suggest that the two types of pulsations may possibly have different exciting mechanisms and or different propagation paths.

The first suggestion that the plane of polarization of pc's undergoes a diurnal variation appeared in 1965 when the Observatory rapid run records were analyzed and it was thus one of the aims of the field work to verify this observation. It is satisfying that the above phenomenon has also been observed by CHRISTOFELL and LINFORD (1966a) from a few days' records taken at Wellington, New Zealand. Their results agree qualitatively with the present observation. It is tempting to identify those morning events with predominantly E-W polarization with DUNGEY's toroidal oscillation in the outer atmosphere and the afternoon events with his poloidal oscillation. If this is done it will imply that the period of the toroidal mode of oscillation as observed in S.W. England is about 33 seconds, while that of the poloidal mode is about 41 seconds. These two modes of oscillation are in general coupled, as was pointed out by DUNGEY. Observations here would suggest that the decoupling of the two modes of oscillation is controlled by local time, such that in S.W. England poloidal oscillations predominate in the afternoon, while in the late morning toroidal oscillations are dominant, but during the night the two modes are of equal intensity.
In this picture no distinction is made between pt's and pc's. The change over from one type of oscillation to another would have to be quite rapid between 10.00 and 12.00 hours. The existence of two simultaneous events of different period, one event being predominantly in one of the horizontal components while the other predominates in the other component seems to support the above interpretation of the observations. Fig. 6.30 is a tracing of a record in which a short period event, (20-30 seconds), has higher amplitudes in the E-W plane than in the N-S plane, while the reverse is the case for the 42 seconds simultaneous event. Though events of this nature were often observed, the difference in the amplitudes of the two signals in each of the components and the variation in their periods made it difficult for one to be too certain of the phenomenon.

The observed variation of the plane of polarization of micropulsations may also be explained if micropulsations originate from travelling magnetic disturbances in the ionosphere or beyond. The change in the pattern of the disturbance, as seen at a recording station, may be expected to give rise to a precession of the polarization. If this explanation is the right one it requires that the frequency of the precessing vector be a function of the time of day. The vector will be such that its direction is generally E-W
FIG. 4.30. SECTION OF RECORD IN WHICH TWO EVENTS ARE SIMULTANEOUSLY PRESENT. THE SHORT PERIOD EVENT HAS LARGER AMPLITUDE IN THE E-W COMPONENT THAN IN THE N-S COMPONENT. THE LONG PERIOD EVENT HAS LARGER AMPLITUDE IN THE N-S THAN IN THE E-W COMPONENT.
in the late mornings and generally N-S in the afternoon, as is brought out in Figs. 6.31a and 6.31b. These are tracings of a part of a record taken on 9th April, 1966. Fig. 6.31a is the morning event while Fig. 6.31b is an afternoon event. In each figure, the horizontal component traces are on the same sensitivity while that of the vertical trace is about three times the sensitivity of the horizontal component traces. The discontinuous character of pc activity makes it experimentally difficult to test the above possible explanation. If the micropulsation field is a precessing vector, then the direction of the major axis of the ellipse of polarization will vary with time of day. As with other parameters of micropulsations, a large amount of statistical data is required to establish the mean direction of the major axis of the polarization ellipse. With a large number of records with many hours of continuous pc activity in the two horizontal components, the determination of the sense and rate of precession of the pc vector may be made as follows. Imagine that the two horizontal components of pulsations are expressed as $X \cos (wt + \phi_1)$ and $Y \cos (wt + \phi_2)$ where $w$ is the angular frequency of the pulsation, $\phi_1$ and $\phi_2$ are the phase angles and $t$ is time. These two vectors can be added and the behaviour of their resultant, $A(t)$, can be examined, for if
Fig. 6.310. A trace of a section of record showing typical morning pulsation with a larger amplitude in the E-W than in the N-S component.
E-W

HARTLAND POINT, 9/4/66

FIG. 631b. A trace of a section of record showing an afternoon pulsation with a larger amplitude in the N-S than in the E-W component.
\[
\bar{A}(t) = \bar{I}_x A_x(t) + \bar{I}_y A_y(t)
\]
where
\[
A_x(t) = X \cos (wt + \psi_1)
\]
\[
A_y(t) = Y \cos (wt + \psi_2)
\]
\[
\bar{I}_x \quad \text{and} \quad \bar{I}_y \quad \text{are unit vectors along the x and y axes respectively}
\]

by eliminating \(t\) from the above equations it is possible to arrive at the relation (c.f. appendix 2)

\[
\frac{A_x^2}{X^2} + \frac{A_y^2}{Y^2} - \frac{2 A_x A_y}{XY} \cos \alpha = \sin^2 \alpha
\]

where
\[
\alpha = \psi_2 - \psi_1
\]

This is the equation of an ellipse whose major axis is inclined at an angle \(\theta\) with respect to the x-axis, given by

\[
\tan 2\theta = \frac{-2XY \cos \alpha}{X^2 - Y^2}
\]

(see appendix 2)

A computer program can easily be written to calculate the average \(\theta\) at time intervals of say 30 minutes. \(\alpha\) may be evaluated from the cross spectra of the two horizontal components, (X and Y), of pulsations, being the angle whose tangent is equal to the ratio of the quadrature spectrum to the cospectrum of the cross spectrum. \(X^2\) and \(Y^2\) may be replaced by their single spectra. A rotation of the plane of polarization of the pulsations will be detected as changes in the value of \(\theta\) with time of day. Both the sense of rotation and its dependence on frequency are easily investigated.

This program may also suggest which of the two possible
explanations for the observations is the right one as the existence of two separate events will be seen as two values of θ, say θ₁ and θ₂ for each event. Both θ₁ and θ₂ will be characterized by a constant value throughout the day. As was remarked earlier, a large number of records showing continuous pc activity for many hours of the day is required for this investigation. To reduce the labour involved, it is desirable to record the pulsation in a form in which the records may be directly fed to a computer.

The observed differences in the amplitude of the horizontal component of pulsations between stations can hardly be explained as due to the sea effect. The abrupt change in the amplitude ratio of the N-S component of pulsations at Shebbear to that at Hartland Point or the Observatory at about 11.00 hours correlates very well with that in the direction of polarization of the pulsations at about the same time. This seems to suggest a sudden change in the orientation of the micropulsation source relative to the stations. The dependence of the amplitude ratio of the pulsations at two stations on the time of day can hardly be explained in terms of geological differences between the stations. In any case a spatial variation of the horizontal component of pulsations is inconsistent with the plane wave model for the pulsation (c.f. chapter 2). It appears therefore that the
pulsations observed in S.W. England arise from a not too distant source. If the sudden change in the amplitude ratio of pulsations at two stations may be interpreted as due to the change in orientation of the micropulsation source, the ionosphere appears to be the likely position of the source since the differences in the orientation of the source are detectable within a distance of about 15 miles. If the source is not in the ionosphere, the results here suggest that a local medium has at least a modifying effect on the recorded pulsations. It is interesting to know that differences in the amplitudes of the horizontal components of pulsations at stations a few tens of kilometres apart have been observed by DUFFUS et al (1962). The differences were thought to be due mainly to geological effects. Unfortunately their results cannot be compared with the observations here because they did not investigate the dependence of the amplitude ratios on local time.

STUART and USHER (1966) have observed that the time of occurrence and period of the most frequently occurring pulsations are different at Lerwick and Hartland. They found that at Lerwick the time of occurrence of maximum activity is about 08.00 hours and the period of pulsations is 3\frac{1}{4} seconds, while at Hartland the period of the predominant event is 40 seconds and maximum activity occurs about 12.00
hours. Now the analysis in this chapter reveals that the period of the predominant event in S.W. England varies with the time of day, being about 33 seconds at about 08.00 GMT, while at noon it is about 41 seconds. These two observations may be explained if micropulsations originate from a rotating source such that different sections of the source configuration oscillate with different frequencies. The rotation of the source would explain the rotation of the micropulsation vector on the earth's surface. The period of the predominant event at any station and at each hour will be that of the section of the source favourably oriented towards the observing station. The existence of more than one event at any instant is also adequately explained. The variation of the micropulsation vectors in a distance of a few tens of kilometres suggests that the source is probably in the ionosphere.

The mechanism by which the proposed source is created cannot be discussed with any confidence. But it is reasonable to assume that such a source configuration may arise from the hydromagnetic oscillation of the geomagnetic field lines in a way similar to that proposed by JACOBS and WATANABE (1964). They proposed that the hydromagnetic oscillation of field lines generates electric currents at high latitudes in the ionosphere where the field lines meet i
Two current vortices are created, one in each of the hemispheres. These currents then leak into the lower latitudes. These authors believe that micropulsations observed in the middle latitudes are due to this cause. Now if different field lines of force have different periods of oscillation, and if the oscillation of each creates currents in the ionosphere, it is not difficult to visualize how a source configuration in which different sections are oscillating at different frequencies could arise. The rotation of the plane of polarization of the pulsations, in this model, may then be due either to the rotation of the earth, in which case the source is fixed relative to the sun, or because the source is moving relative to the sun, or both. To investigate whether the diurnal variation of the pulsation vector is due to the rotation of the earth, it may be helpful to determine the major axis of polarization of the magnetic field of a known ionospheric source such as the Sq current system by the method suggested here. The diurnal variation of the vector should then be compared with that which has been observed for micropulsations. If the model proposed here is close to reality, it is obvious that it requires measuring at least two orthogonal components of the pulsation if correct information regarding their periods and polarization at any station is to be obtained. The above model may offer
an explanation why the search for dependence of periods of pulsations on latitude has been inconclusive, since most of the observers have either used a total field or a single component instrument. Like other models, the above cannot explain all the observed characteristics of micropulsations but it appears satisfactory in explaining the results of this study.

Several inferences and conclusions may be drawn from the discussion in this study.

1. The differences in the amplitudes of the vertical component of pulsations at the three British Observatories can satisfactorily explain the energy differences between pulsations at the observatories, observed with total field instruments.

2. The larger part of the observed vertical component of pulsations at Hartland and Lerwick is due to the sea effect.

3. An intrinsic vertical component of pulsations occurs at each place.

4. It has been observed that near the coast at Hartland the in phase and anti-phase vectors of pulsations tend to lie in a fixed plane. This observation extends the period range covered by PARKINSON.

5. Maximum pc activity in S.W. England occurs when the
pc period is shortest. The pt period is longest
during the time of its maximum activity.

6. The plane of polarization of micropulsations under-
goess a diurnal variation.

7. The variation with time of day of the ratio of the
amplitudes of simultaneous pulsations at two loca-
tions can hardly be explained in terms of geological
differences at the two stations. This and the
deduced existence of an intrinsic vertical component
of pulsations suggest that the pulsations originate
from a not very distant source whose orientation
varies between stations a few tens of kilometres
apart.

8. A rotating, possibly ionospheric, source whose period
of oscillation varies along the source configuration
seems satisfactory in explaining the differences in
the properties of pulsations in Britain and S.W.
England in particular.

9. A study of the dependence of the period of pulsation
requires recording at least two orthogonal hori-
zontal components of pulsations simultaneously at
stations spread over the range of latitude of interest.

10. Because of differences in the occurrence, planes of
polarization, period characteristics and wave shapes
pt's and pc's are either unrelated phenomena or else their excitation mechanism and or propagation paths are different.
APPENDICES
APPENDIX 1

Lower Limit

a. Ratio Positive

\[ \left| \frac{Z_s}{Z_o + Z_s} \right| > \frac{8}{10} \]

i.e.

\[ \frac{Z_s}{Z_o + Z_s} > \frac{8}{10} \]

10Z_s > 8(Z_o + Z_s)

2Z_s > 8Z_o

\[ \frac{Z_s}{Z_o} > 4 \]

\[ \frac{Z_s + Z_o}{Z_o} > 5 \]

\[ \frac{Z_o}{Z_s + Z_o} < \frac{1}{5} \]

b. Negative Ratio

i.e. \[ \frac{Z_s}{Z_o + Z_s} \] is negative

This can only be so if Z_o and Z_s are of opposite sign and if Z_o > Z_s. But Z_o > Z_s is not consistent with a rapid decrease of (Z_o + Z_s) away from the coast since Z_o is assumed constant. Hence a negative value of the ratio \( Z_s/(Z_s + Z_o) \) is untenable.

Upper Limit

\[ 1 < \left| \frac{Z_s}{Z_o + Z_s} \right| < \frac{13}{10} \]
(a) A negative value will again imply that $Z_0$ and $Z_s$ are of opposite reign and $Z_0 > Z_s$. As above this is untenable.

(b) Positive Upper Limit

$$1 < \frac{Z_s}{Z_s + Z_o} < \frac{13}{10}$$

This situation will only arise if $|Z_s| > |Z_o|$ but $Z_s$ and $Z_o$ must be of opposite sign for the ratio $(Z_s/Z_s + Z_o)$ to be greater than 1.

i.e. $$\frac{Z_s}{Z_s - Z'_o} = \frac{13}{10}$$

where $Z'_o = -Z_o = |Z_o|

i.e. $$\frac{Z_s}{Z_s + Z_o} = \frac{Z_s}{Z_s - Z'_o} < \frac{13}{10}$$

$$10Z_s < 13Z_s - 13Z'_o$$

$$13Z'_o < 3Z_s$$

$$\frac{13}{3} < \frac{Z_s}{Z'_o}$$

$$\frac{10}{3} < \frac{Z_s - Z'_o}{Z'_o}$$

$$\left| \frac{Z_s - Z'_o}{Z'_o} \right| = \left| \frac{Z_s + Z_o}{Z_o} \right| > \frac{10}{3}$$

i.e. $$\left| \frac{Z_o}{Z_s + Z_o} \right| < \frac{3}{10}$$
APPENDIX 2

The general equation of a conic possessing a centre is given by

$$ax^2 + 2hxy + by^2 + c = 0$$  \hspace{1cm} (1)

if the centre is the origin of the coordinates, (Mathematical Methods in Science and Engineering by J. HEADING, p 193). It can be shown that the conic represents an ellipse if

$$ab - h^2 > 0.$$  \hspace{1cm} (2)

The axes ox, oy are directed along the principal axes of the conic if the coefficient of xy, i.e. $h$, vanishes, i.e. the equation of the conic becomes

$$ax^2 + by^2 + c = 0.$$  

Now consider the equation of a central conic with its centre at the origin and its principal axes along the coordinate axes. It is given by

$$ax^2 + by^2 + c = 0.$$  \hspace{1cm} (3)

Let new axes $ou$, $ov$ be chosen, obtained respectively from $ox$, $oy$ by rotation through an angle $\theta$ in the positive sense.
Now
\[ x = u \cos \theta - v \sin \theta, \quad y = u \sin \theta + v \cos \theta. \]
Equation (3) in the new coordinate system becomes
\[ a(u \cos \theta - v \sin \theta)^2 + b(u \sin \theta + v \cos \theta)^2 + c = 0. \]
i.e. \[ u^2(a \cos^2 \theta + b \sin^2 \theta) + v^2(a \sin^2 \theta + b \cos^2 \theta) + 2uv[\sin \theta \cos \theta(b - a)] + c = 0. \] (4)
(4) is thus an equation of a conic whose principal axes are inclined by an angle \( \theta \) to the coordinate axes, and the centre of the conic is the origin of the coordinates. Use will be made of equation (4) later.

Consider the two orthogonal components of the time-varying vector field given by \( X \cos(\omega t + \varphi_x) \) and \( Y \cos(\omega t + \varphi_y) \) where \( \omega \) is the angular frequency of the vector and \( \varphi_x \) and \( \varphi_y \) are the phase angles and \( t \) is time. \( X \) is directed along the \( ox \) axis while \( Y \) is directed along the \( oy \) axis. The vector field, \( \vec{A}(t) \), at any instant \( t \) is given by the vector sum of the components, i.e.
\[ \vec{A}(t) = \vec{i}_x A_x(t) + \vec{i}_y A_y(t) \]
where
\[ A_x = X \cos(\omega t + \varphi_x) \] (5)
\[ A_y = Y \cos(\omega t + \varphi_y) \] (6)
and \( \vec{i}_x, \vec{i}_y \) are unit vectors along the \( x \) and \( y \) axes respectively.
From equations (5) and (6) we have respectively
\[ A_x/X = \cos \omega t \cos \varphi_x - \sin \omega t \sin \varphi_x \] (7)
and \[ A_y/Y = \cos \omega t \cos \varphi_y - \sin \omega t \sin \varphi_y \] (8)
Multiplying both sides of equation (7) by \( \cos \varphi_2 \) and both sides of equation (8) by \( \cos \varphi \) and on subtracting it is found that

\[
A_x/X \cos \varphi_2 - A_y/Y \cos \varphi = \sin \omega t \sin (\varphi_2 - \varphi) \tag{9}
\]

Similarly by multiplying both sides of equation (7) by \( \sin \varphi_2 \) and both sides of equation (8) by \( \sin \varphi \) and subtracting it is found that

\[
A_x/X \sin \varphi_2 - A_y/Y \sin \varphi = \cos \omega t \sin (\varphi_2 - \varphi_1) \tag{10}
\]

Squaring both sides of equations (9) and (10) and adding it is found that

\[
\frac{A_x^2}{X^2} + \frac{A_y^2}{Y^2} - \frac{2A_xA_y}{XY} \cos (\varphi_2 - \varphi) = \sin^2(\varphi - \varphi) \tag{11}
\]

Since \( \frac{1}{X^2} \times \frac{1}{Y^2} > \frac{\cos(\varphi_2 - \varphi_1)}{X^2Y^2} \) (if \( \varphi_2 \neq \varphi_1 \))

by comparison with the relation in (2), it is obvious that equation (11) is an equation of an ellipse. If \( \varphi_2 = \varphi \), equation (11) becomes the equation of a straight line through the origin whose slope is \( Y/X \). The angle between the principal axis of the ellipse and the \( x \)-axis may be found by comparing equations (11) and (4). From the two equations we have

\[
\frac{1}{X^2} = a \cos^2 \theta + b \sin^2 \theta
\]
\[
\frac{1}{Y^2} = a \sin^2 \theta + b \cos^2 \theta
\]
\[
\cos \left( \varphi - \varphi \right) = -\sin \theta \cos \theta (b - a)
\]
\[
\frac{X^2 - Y^2}{X^2Y^2} = b(\cos^2\theta - \sin^2\theta) - a(\cos^2\theta - \sin^2\theta) = \cos 2\theta (b - a).
\]

\[
\cos(\varphi_2 - \varphi_1) \cdot \frac{X^2Y^2}{X^2 - Y^2} = \frac{\sin \theta \cos \theta (b - a)}{\cos 2\theta \times (b - a)} = \frac{1}{2} \tan 2\theta.
\]

i.e. \( \tan 2\theta = \frac{2XY \cos \alpha}{(X^2 - Y^2)} \)

where \( \alpha = \varphi_2 - \varphi_1 \)
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