Very Low Frequency Electromagnetic Phenomena: 'Whistlers' and Micropulsations

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Very low frequency electromagnetic phenomena: 'whistlers' and micropulsations

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[Plate 1]

Observations of natural electromagnetic phenomena, embracing frequencies ranging from millihertz to tens of kilohertz, have made a major contribution to our knowledge of the terrestrial environment extending out to many Earth's radii. The Antarctic has offered exceptional opportunities in this field for a number of reasons, including: (i) the location of Antarctic bases (including Halley Bay) at key magnetic latitudes, (ii) magnetic conjugacy to Northern Hemisphere thunderstorm sources, (iii) low interference levels.

Important aspects of this research are the investigation of the rôle of wave–particle interactions in the magnetosphere and that of the structure and dynamical behaviour of the plasmapause, using both passive and active techniques. Comparisons of observations made at antarctic stations and their northern geomagnetic conjugates show close similarities in dominant pulsation periods and demonstrate the uniqueness of the Weddell Sea area in relation to magnetospheric wave amplification at the higher frequencies.

An extra dimension to this work is being added, during the International Magnetospheric Study (1976–8), through the development of a chain of stations employing the goniometer (direction-finding) technique pioneered at Halley Bay by Sheffield University.

Introduction

The term 'very low frequency' in the title is used to refer to electromagnetic signals with frequencies in the tens of kilohertz range and below. The designations v.l.f., e.l.f. and u.l.f. are used explicitly, however, for the regions of the electromagnetic spectrum 3–30 kHz, 300 Hz–3 kHz and below 300 Hz respectively and the work described here extends over this complete spectrum.

Such electromagnetic waves populate the magnetosphere, where they interact with the energetic charged particles which are trapped by the Earth's magnetic field. Thus their study is important in revealing the rôle of wave particle interactions in the magnetosphere, involving processes of wave amplification and particle precipitation into the upper atmosphere. Observations of these electromagnetic phenomena also provide a powerful diagnostic tool for studying the structure and dynamical behaviour of the magnetospheric plasma.

The magnetosphere, schematically illustrated in figure 1, is formed through the interaction of the solar wind with the Earth's magnetic field and is populated with plasma having a wide range of densities and energies, the latter ranging from the thermal energy of plasma derived from the ionosphere to the high energy electrons and protons of the radiation belts. The magnetosphere extends approximately ten Earth's radii towards the Sun and to beyond the lunar orbit in the anti-solar direction.

An important feature is the plasmapause, located on a magnetic shell with $L \approx 4$ (in conditions of low magnetic disturbance).† The region inside the plasmapause, termed the plasmasphere, is populated by thermal plasma diffusing upwards from the ionosphere and co-rotating with the Earth. The much lower density plasma external to the plasmapause convects towards the sunward magnetopause boundary. Figure 2 shows the plasmapause boundary as determined from v.l.f. whistler observations. Figure 3 shows, schematically, the electric equipotentials in the equatorial plane of the magnetosphere and it is along these that the magnetospheric plasma convects (in the direction of the arrows). The last closed equipotential (solid line) is the plasmapause. The difference between the observed plasmapause of figure 2 and the idealized one of figure 3 is, in part, due to the variation in ionospheric conductivity. Much of the work described in the later sections relates to the study of the structure and dynamical properties of the plasmapause boundary and of the magnetospheric electric field.

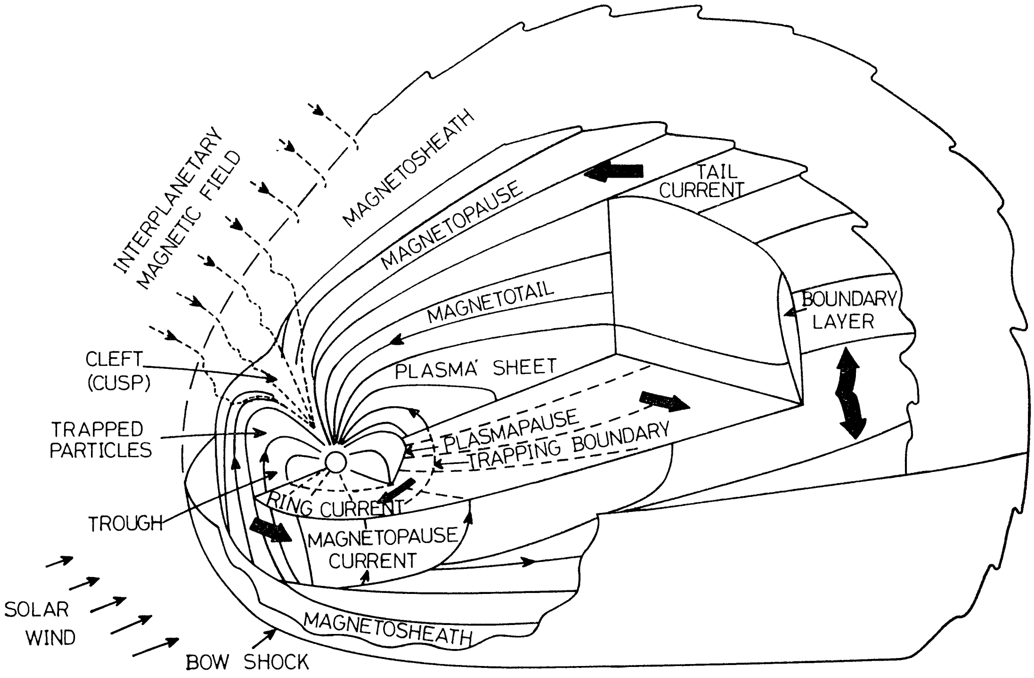

Figure 1. Schematic illustration of the structure of the magnetosphere (after Heikkila 1972).

V.l.f., e.l.f. and u.l.f. (micropulsation) studies in Antarctica will contribute to a major extent in the International Magnetospheric Study (I.M.S.) during the period 1976–8.

The paper is divided into two parts dealing with v.l.f./e.l.f. phenomena and micropulsations respectively.

V.L.F./E.L.F. PHENOMENA

(a) *Classification*

Many different types of v.l.f. signal may be observed by a ground-based receiver (Helliwell 1965). Whistlers and v.l.f. emissions, such as chorus and hiss, are naturally generated signals which are of great importance in magnetospheric physics. Man-made signals are radiated from v.l.f. communications and navigational transmitters, and power lines (see § *e*).

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† The L-value of a magnetic shell is essentially its equatorial distance, measured in Earth's radii, from the centre of the Earth.

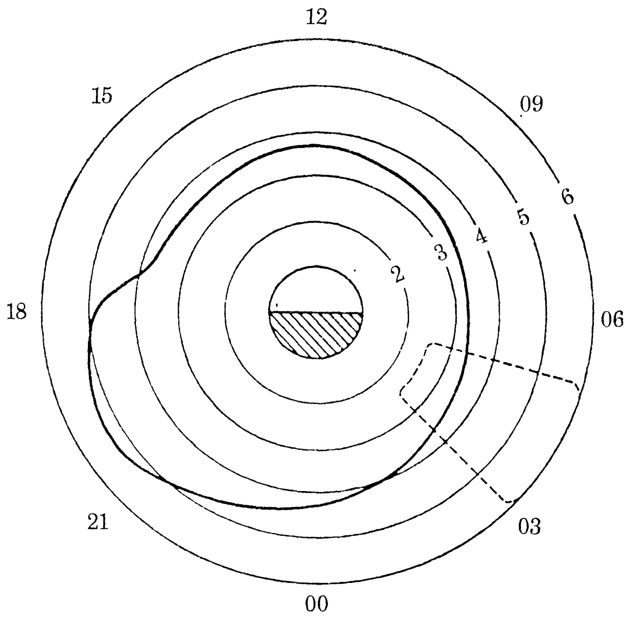


Figure 2. The location of the plasmapause in quiet magnetic conditions (from Carpenter 1970). Coordinates are L and magnetic local time.

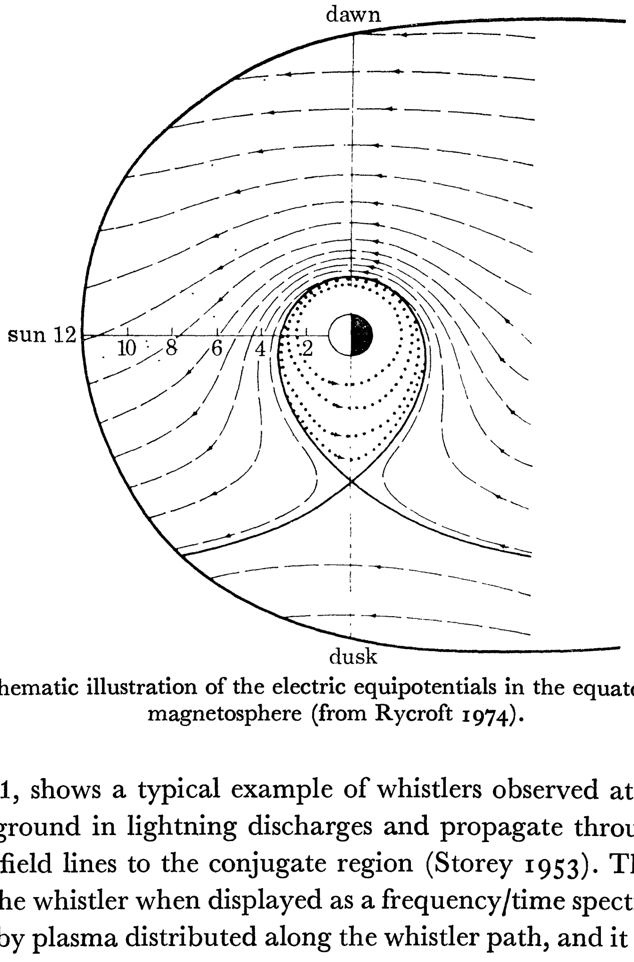


Figure 3. Schematic illustration of the electric equipotentials in the equatorial plane of the magnetosphere (from Rycroft 1974).

Figure 4*a*, plate 1, shows a typical example of whistlers observed at Halley Bay. Whistlers originate near the ground in lightning discharges and propagate through the magnetosphere along geomagnetic field lines to the conjugate region (Storey 1953). The characteristic quasi-parabolic shape of the whistler when displayed as a frequency/time spectrogram, as in figure 4*a*, is due to dispersion by plasma distributed along the whistler path, and it is possible to determine plasma densities in the magnetosphere by measurements of whistler dispersion (Carpenter 1962). Furthermore, the *L*-value of the field line along which the whistler has travelled may be deduced from its 'nose' frequency (Helliwell, Crary, Pope & Smith 1956), i.e. the frequency for which the group delay time is a minimum. Thus whistler measurements provide a valuable ground-based method for probing the structure and dynamics of the magnetosphere (Carpenter 1970).

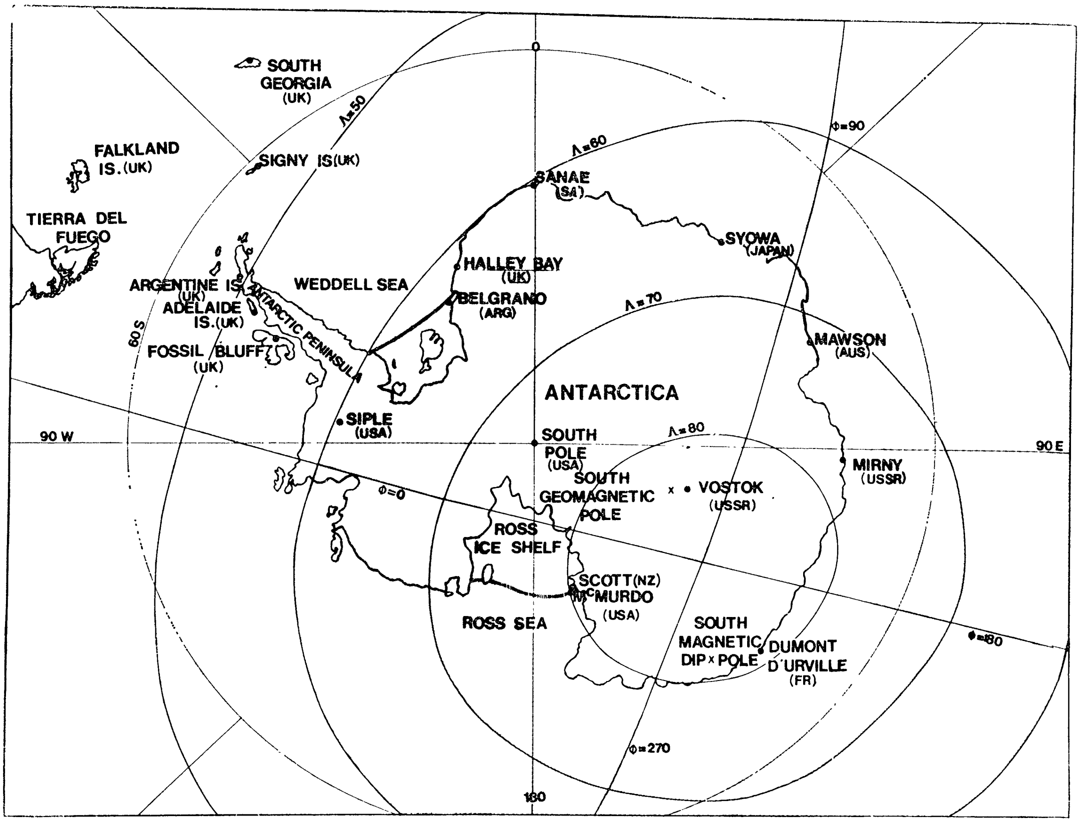
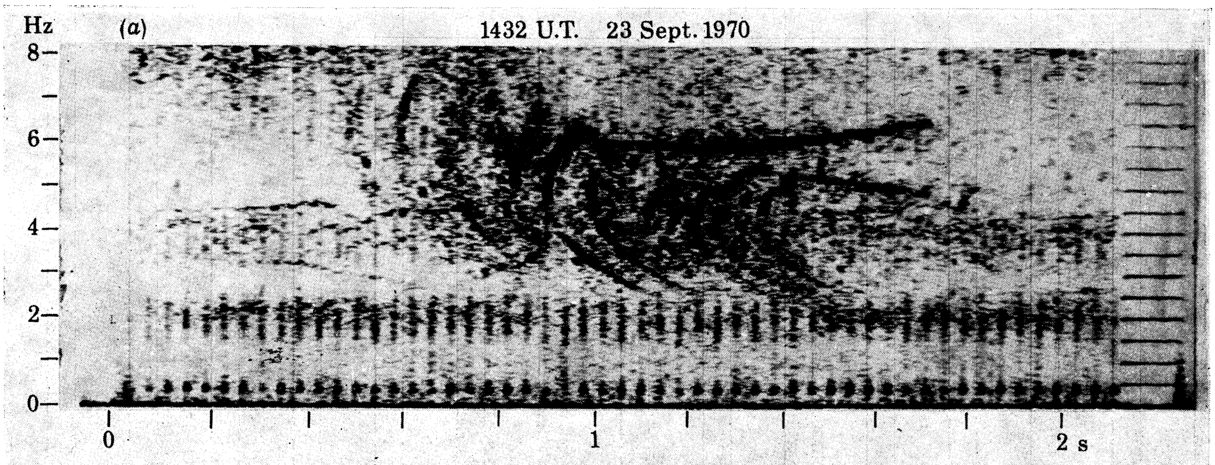


FIGURE 5. Location of antarctic stations in geographic and geomagnetic invariant latitude and longitude (Λ, Φ).

Discrete v.l.f. emissions are whistler-mode waves generated in the magnetosphere by resonant interactions with radiation belt electrons (Helliwell & Crystal 1973). An example of discrete emissions observed at Halley Bay is shown in figure 4*b*. Such emissions may be generated spontaneously as in this example, or triggered by whistlers (as in figure 4*a*) or by man-made transmissions (Helliwell 1965). V.l.f. emissions in the magnetosphere have been reviewed by Rycroft (1972).

Figure 4*b* shows signals at 10.2 and 11.33 kHz from the Omega transmitter in North Dakota, U.S.A., which have travelled by sub-ionospheric propagation. The amplitude of such signals can change appreciably with the incidence of whistlers (Helliwell, Katsufrakis & Trimpi 1973). Man-made signals (from v.l.f. transmitters) may also propagate in the whistler mode and such signals are frequently amplified in the magnetosphere by resonant wave–particle interactions, in some cases by as much as 30 dB (Helliwell 1975; Bullough *et al.* 1975; Helliwell 1976).



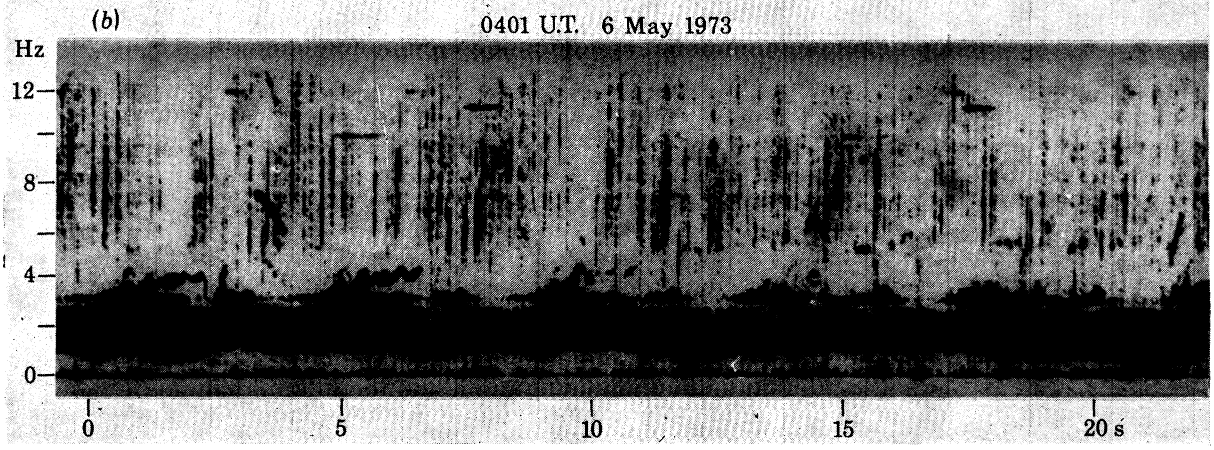


FIGURE 4*a*. Spectrogram of whistlers observed at Halley Bay. Pronounced triggered emissions can be seen commencing at the upper frequency limit of two of the whistler components.

FIGURE 4*b*. Spectrogram of discrete v.l.f. emissions observed at Halley Bay. Constant frequency signals at 10.20 and 11.33 kHz originate from an Omega radio navigation transmitter.

(*b*) *The importance of Antarctica for v.l.f. observations*

V.l.f. observations in Antarctica, particularly at stations such as Halley Bay in the Weddell Sea sector (see figure 5), are extremely valuable for a number of reasons.

Firstly, the whistler occurrence rate is very high, especially during the antarctic winter, because the high incidence of thunderstorms in the conjugate region of eastern Canada provides a plentiful source of whistlers and also because D-region absorption of down-going whistler signals in the south is small during the long winter hours of darkness.

Secondly, stations such as Siple, Halley Bay, Belgrano and Sanae lie close to 60° invariant geomagnetic latitude ($L = 4$) and thus are ideally situated for studies of the plasmapause which normally lies at about this L-value (figure 2).

Thirdly, Antarctica provides an environment relatively free from the kind of interference which often obscures v.l.f. observations at less isolated locations. The lack of any thunderstorm activity means there are no locally generated sferics, and the level of man-made interference is also potentially very low.

(*c*) *Whistler observations of the plasmapause and magnetospheric electric fields*

Whistlers propagate along ducts of enhanced plasma density aligned along geomagnetic field lines. By measuring f_n and t_n, the nose frequency and nose time delay of a whistler, it is possible to determine the L-value of the field line along which it has propagated, and also the electron density at the point where it crossed the equatorial plane (Park 1972). For the former, it is sufficient to know the electron gyrofrequency at the equator f_{HE} (proportional to L^{-3}). This can be determined by the approximate proportionality relationship $f_{HE} = f_n/\Lambda_n$ where Λ_n is almost independent both of L and of the electron density distribution model assumed, having a value of about 0.38. In the case of a non-nose whistler, f_n and t_n are not directly observable but may be calculated using one of various extrapolation techniques (Bernard 1973; Smith, Smith & Bullough 1975).

A multi-path whistler is observed when energy from a single lightning discharge travels in several different ducts having a range of L-values; this is the type of whistler most commonly observed at antarctic stations such as Halley Bay (figure 4*a* shows an example). By measuring f_n and t_n for each component of the multi-path whistler it is possible to map out the radial distribution of equatorial electron density in the magnetosphere. Figure 4*a* shows the general tendency for the propagation time to increase with decreasing nose frequency and hence with increasing L; this is because of the longer path lengths at greater L.

The plasmapause, the boundary across which the magnetospheric plasma density drops sharply, typically from 10^9 m^{-3} inside to 10^7 m^{-3} outside for a 0.1 change in L, was first discovered by Carpenter (1963) using the whistler method. He observed the relatively rarely occurring 'knee whistler', so-called because its path is outside the 'knee' in the electron density distribution (i.e. the plasmapause). The knee whistler has an anomalously short travel time, compared to a whistler with a similar path length inside the plasmapause, because the lower electron density along the path results in a greater group velocity.

The study of the structure and dynamics of the plasmapause is of great importance in understanding magnetospheric processes. Although the plasmapause has been observed directly by satellites (Chappell 1972), the ground-based whistler method remains a very effective way of observing the plasmapause (Carpenter 1966; Angerami & Carpenter 1966).

Electric fields in the magnetosphere can also be deduced from measurements of whistlers observed on the ground (Carpenter, Stone, Siren & Crystal 1972). A steady electric field $\boldsymbol{E}$ at right angles to the magnetic field $\boldsymbol{B}$ causes the plasma, and hence any whistler duct paths, to drift with a velocity $(\boldsymbol{E} \times \boldsymbol{B})/B^2$. The east–west component of this electric field causes a radial motion of the ducts which can be detected by a change in nose frequency of whistlers travelling along a duct as its L-value changes. If the same ducts are excited in a series of successive multipath whistlers, the radial motion of each duct may be plotted and the east–west component of the electric field may be deduced as a function of time and L (Sagredo, Smith & Bullough 1973). The high whistler rates found near Halley Bay give exceptionally good time resolution of changes in the electric field.

(*d*) *The goniometer technique*

The whistler method outlined above has an important shortcoming in that the L-value of the field aligned whistler duct path can be determined but not the longitude of the whistler path. However this can be inferred to some extent from the intensity of the whistler signal since it suffers attenuation in travelling in the Earth-ionosphere waveguide to the receiver from the exit point, i.e. the point at the base of the ionosphere at which the whistler signal enters the waveguide. Intense whistlers tend to have exit points very close to the receiver.

In his work on whistler data from Eights and Byrd, Carpenter (1966) assumed that the exit points lay within 15° of each side of the station. This figure is consistent with recent (unpublished) comparisons of data recorded at Siple (76° S, 84° W) and Halley Bay (75.5° S, 26.6° W) in which it was found that about 30 % of whistlers observed at one of these stations was observed simultaneously at the other. The two stations are 1500 km apart – a difference in magnetic longitude of about 25°.

This lack of longitude information means poor local time resolution in locating the plasmapause and also the inability to detect longitudinal drifts of whistler ducts and hence measure the equatorial radial electric fields associated with them. This problem can be overcome by use of the goniometer technique to measure the direction of arrival of whistler signals.

The goniometer direction-finding technique, using a rotating loop aerial, was first described by Ellis & Cartwright (1959) and by Watts (1959). The method assumes that the received whistler signal is in the transverse magnetic waveguide mode with the magnetic vector horizontal and transverse to the direction of propagation. Thus a loop aerial rotating about a vertical axis modulates the signal at the loop rotation frequency, and the direction of the signal can be determined by measuring the phase of the modulation (Bullough & Sagredo 1973).

Goniometer studies of whistler data recorded at Halley Bay have been made by Bullough & Sagredo (1970) and Sagredo & Bullough (1973). Figure 6 shows a plot of whistler exit points observed at Halley Bay and demonstrates the existence of longitudinal structure in the plasmapause. The four different knee whistler ducts observed ($K1$, $K2$, $K3$, $K4$ in figure 6) had electron tube contents varying by a factor of 3 over 12° of invariant longitude. Furthermore, on this particular occasion, all the non-knee whistler ducts were located in a narrow strip which was observed to remain fixed with respect to Halley Bay over an 18 h period and hence to co-rotate with the Earth. Such longitudinally localized co-rotating structure in the plasmasphere is probably related to co-rotating zones of v.l.f. emissions observed by satellites (Lefeuvre & Bullough 1973).

In order to locate the whistler exit point for the Halley Bay observations mentioned above

(Bullough & Sagredo 1973), the whistler nose frequencies were used to determine the L-values of their paths (see § *c*). A better method is to use a network of two or more stations to obtain triangulation fixes on the exit points. This approach was used by Rycroft, Jarvis & Strangeways (1975) in Canada who found from two-hop whistler measurements that the L-values of whistler duct exit points determined by triangulation, were consistently lower by about 0.7 than the equatorial L-values of the ducts determined from the whistler nose frequencies. Such a result is clearly of great importance in the interpretation of whistler data, and underlines the need for more whistler observations using networks of goniometer stations.

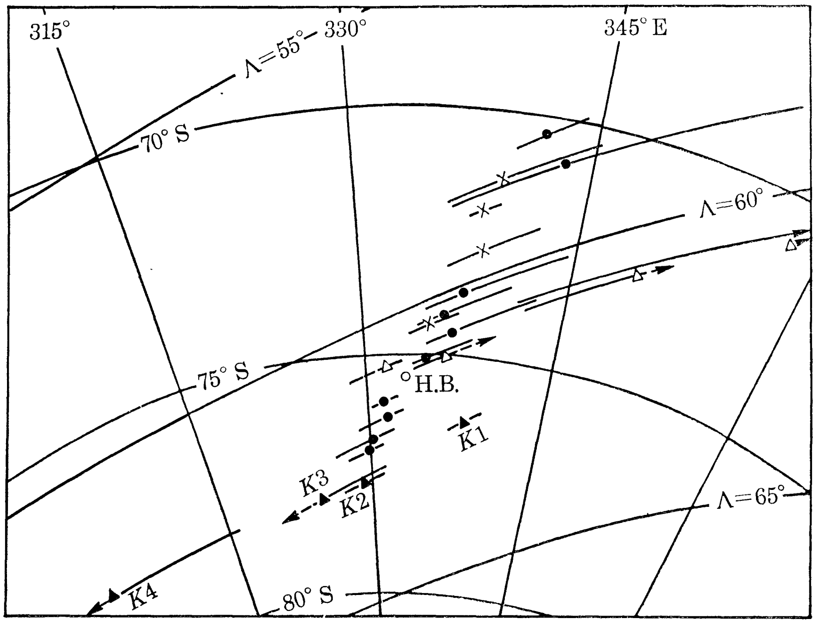


FIGURE 6. Location of whistler exit points determined at Halley Bay, 26 July 1967 (from Sagredo & Bullough 1973).

The establishment of a network of v.l.f. goniometer stations in Antarctica for the I.M.S. is clearly desirable, and it is hoped to establish a chain of goniometer receivers near $L = 4$ in the Antarctic at stations such as Siple, Halley Bay and Sanae (70.3° S, 2.4° W). These will be capable of determining large scale structure in and near the plasmapause. In addition it is planned to establish an unmanned goniometer station designated Seal (Sheffield e.l.f./v.l.f. Antarctic Laboratory) about 100 km to the south of Halley Bay. Triangulation measurements of whistler exit points using the Halley Bay/Seal baseline should be capable of resolving fine structure in the Halley Bay sector.

(*e*) *Magnetospheric amplification of man-made v.l.f. signals*

A full description of this subject is given by Helliwell (1977) in this volume and elsewhere (Helliwell & Katsufrakis 1974).

Similar effects have been observed, apparently generated by harmonics from a.c. electric power lines which are radiated into the magnetosphere (Helliwell, Katsufrakis, Bell & Raghuram 1975). Some results from the Ariel 3 and 4 satellites are summarized in figure 7 (see also Bullough, Tatnall & Denby 1976), which shows the intense zone of emissions over the U.S.A.

and its conjugate zone west of the Antarctic Peninsula, caused at least partly by power line harmonic radiation. Earlier work by Bullough *et al.* (1975) has shown that strong magnetospheric amplification is more frequent in this longitude sector than others. The map also shows the zone of emissions partly due to power line harmonic radiation from Europe to eastern U.S.S.R., with its conjugate image in the Southern Hemisphere. In the top left-hand corner of the map there is an unexplained separate peak in the emissions located over Spitzbergen.

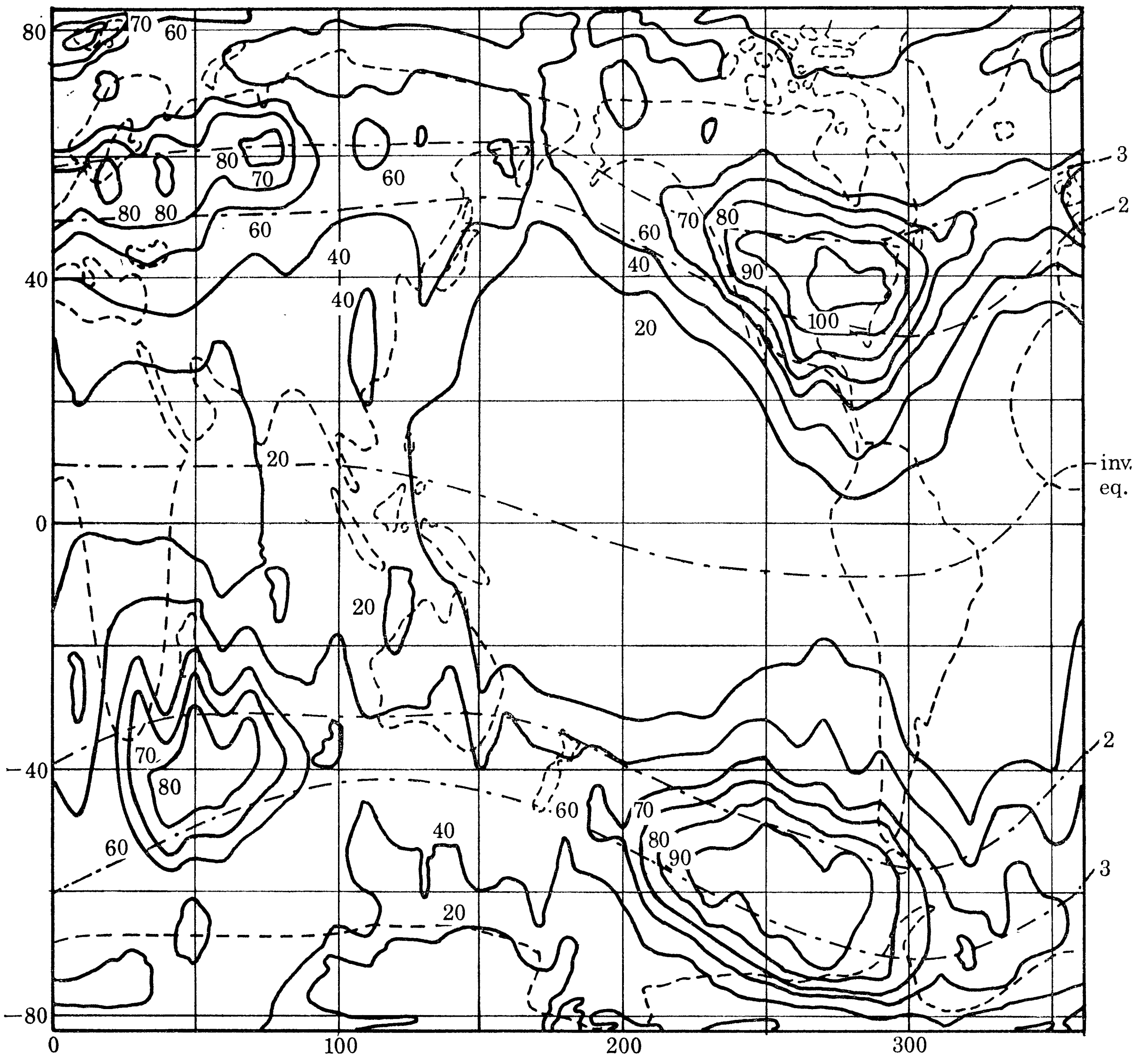


FIGURE 7. Occurrence of v.l.f. emissions observed on the Ariel 4 satellite at 3.2 kHz, 20 March–24 June 1972. The contours give the percentage probability of observing emissions stronger than 4.8×10^{-16} W m^{-2} Hz^{-1} for periods of magnetic quiet ($K_p \leqslant 2+$). – – –, World map; –·–·–, magnetic invariant equator and contours of $L = 2$ and 3 at satellite altitude. Coordinates are geographic.

Geomagnetic pulsations

(a) *Geomagnetic pulsations within the magnetosphere*

A remarkable variety of magnetic disturbances are observed at the Earth's surface and on board satellites by sensitive magnetometers. Many of these disturbances are quasi-sinusoidal in appearance and have been attributed to hydromagnetic waves within the magnetosphere, for example, see reviews by Orr (1973, 1975), Lanzerotti & Fukunishi (1974) and a book by Jacobs (1970).

These geomagnetic pulsations have been conveniently classified into two main groups Pc and Pi; Pc refers to waves of a mainly continuous character; the oscillations sometimes persist with approximately constant period for several hours. Pi refers to pulsation events which are of shorter duration (typically less than 10 min) and are often irregular: these events are detected most clearly around local midnight. The Pc classification is subdivided into five categories according to the dominant period, covering the range 0.2–600 s. Pi 1 and Pi 2 refer to the ranges 1–40 and 40–150 s respectively.

From ground-based magnetometer array studies, it has become clear that the hydromagnetic wave amplitudes are preferentially enhanced at particular latitudes. This localization of wave energy is consistent with the idea of geomagnetic field line resonance (Southwood 1974; Chen & Hasegawa 1974). Observational evidence has been given for amplitude enhancements both within the plasmasphere and in the plasmatrough (Lanzerotti, Fukunishi & Chen 1974; Orr & Webb 1975; Webb & Orr 1975). The polarization patterns observed suggest that the oscillations are often standing hydromagnetic waves in a guided mode within the magnetosphere. In addition, the period of the waves at the location of the maximum amplitude is related to the magnetospheric plasma density along the geomagnetic field line linking the position of maximum amplitude with the conjugate point in the other hemisphere.

Most geomagnetic pulsation measurements have been made in the Northern Hemisphere; in the next two sections we attempt to summarize the data that have been collected at the British Antarctic Survey station at Halley Bay and compare the observations with those made at its approximately conjugate point, St Anthony in northern Newfoundland and with other stations.

(b) *Continuous pulsations recorded at Halley Bay*

Westwood (1967) from a study of four solsticial months in 1963 and 1964, using fluxgate magnetometers, showed that continuous pulsations in the period range 20–80 s were most frequently recorded just before local noon.

The fluxgate records for one winter month (June), one equinoctial month (September) and one summer month (December) of 1963 were analysed by Finlayson (1967); Pc 3 in the period range 20–40 s was the dominant pulsation. The La Cour magnetograms over several years were inspected for longer period oscillations in the range 100–600 s. A significant peak was found at 175 ± 25 s.

In 1971, rubidium vapour magnetometers designed by I.G.S. (Stuart 1971) were installed at Halley Bay. Since that time approximately 10 months of chart records have been inspected and a bulletin of events prepared; May 1971 and July to October 1971 (Smith 1971) and August to December 1972 (telexed messages from A. J. Smith 1972). Each half hour of continuous activity in the period range 10–150 s (Pc 3 and Pc 4) was recorded as one event and the average frequency of occurrence spectra for the eight different 3 h intervals through the day are presented in figure 8. It shows that from 06 to 21 h U.T. (approximately 03 to 18 h local time) the most frequently observed continuous pulsation is in the period range 25–45 s. Around local 'midnight' an increase in the occurrence of shorter events is noted.

These results are also presented in figure 9 as contour maps of the normalized frequency of occurrence of Pc 3 and Pc 4 in terms of time of day and average night-time K_p index.

Pc 5 pulsations with periods between 150 and 600 s were detected infrequently; approximately 120 events in 10 months records. The activity tends to concentrate into two peaks; one in the morning with an average period of 310 s and the other in the late afternoon with a period of 185 s.

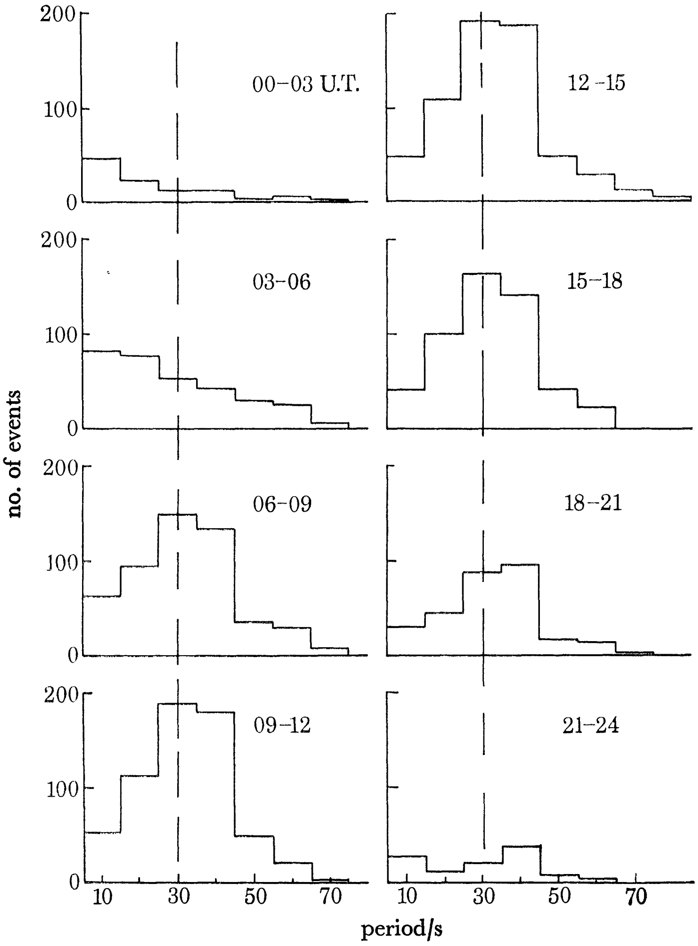


FIGURE 8. Histograms from 10 months of Halley Bay data showing the number of continuous pulsation events against the dominant pulsation period for different 3 h intervals through the day.

(c) *Discussion of Halley Bay records compared with Northern Hemisphere observations*

The geographic coordinates of Halley Bay are 75.52° S and 26.62° W and the corrected geomagnetic coordinates from Akasofu & Chapman (1972) are 61.18° S and 27.69° W.

The L-value for a point 400 km vertically above the observatory is 4.6 (Barrish & Roederer 1969); the geomagnetic field line passing through this point will intersect a similar point in the opposite hemisphere over northern Newfoundland approximately 1° south of St Anthony. This magnetic field line will be associated with the plasmatrough on some occasions and with the plasmasphere for most of the remainder of the time. The plasma density along the magnetic field line (and therefore the characteristic period of a guided standing wave pulsation) will depend on the level of magnetic activity and the time of day. A method of analysis has been developed (Orr & Webb 1975; Roth & Orr 1975; Orr 1975) which allows geomagnetic pulsation occurrence statistics to be plotted in a form which indicates whether the observatory field line is associated with the plasmasphere, the plasmapause or the plasmatrough when the maximum number of events of a particular class of pulsation are detected. The method uses OGO 5 measurements of the plasmapause (Chappell 1972) to predict the average night-time K_p value required to cause the plasmapause to line up with the observatory L shell at different times in the day. This plasmapause overhead position is shown for Halley Bay in figure 9; on average,

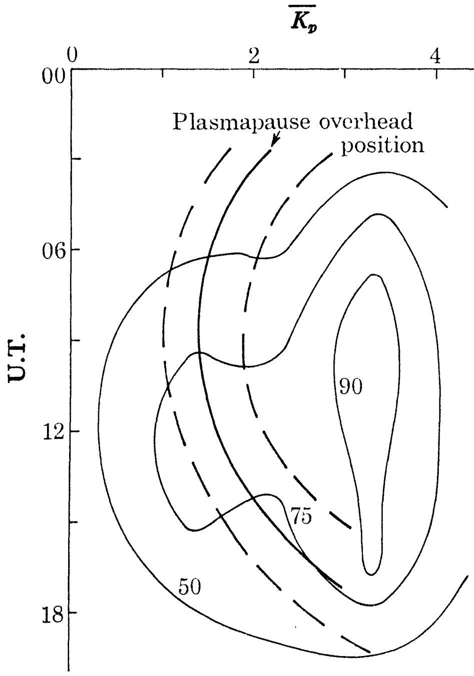


FIGURE 9. Contour map of the normalized frequency of occurrence of pulsation events in the 10–150 s range in terms of day and average night-time K_p index for Halley Bay. Three contours are drawn, corresponding to 90, 75 and 50% of the maximum normalized frequency of occurrence. The bold line corresponds to the plasmapause overhead position for the observatory and the parallel dotted lines to the upper and lower bounds on this estimate.

pulsation events which are plotted to the left of the plasmapause overhead line correspond to occasions when the L shell associated with the observatory is within the plasmasphere. The contour map shows that most Pc 3, 4 events occur when Halley Bay is a plasmatrough station; geomagnetic pulsations, with period centred on approximately 35 s, are detected with the highest probability when the night-time K_p index has averaged about 3. Orr & Webb (1975), from a study of pulsations recorded at five Northern Hemisphere stations, showed that the peak occurrence of Pc 3 is at 08h45 ± 1 h L.T. and is related to the observatory L value and the average night-time K_p index by the equation $L = 8.1–1.2K_p$. For Halley Bay, $L = 4.6$, this equation predicts a K_p value of just under 3 for maximum Pc 3 occurrence (close to the observed value from figure 9) and the time of most frequent occurrence is around 09 h local time, again in good agreement with St Anthony and other Northern Hemisphere stations.

Under typical quiet conditions, the fundamental toroidal period of hydromagnetic waves in the magnetosphere for different L shells has been calculated (Orr 1975). At $L = 4.6$, under quiet conditions, the Halley Bay L shell will be within the plasmasphere throughout the day and the period varies within the range 160–260 s. Thus it seems possible that some of the Pc 5 observed at Halley Bay are either standing hydromagnetic waves excited or enhanced within the plasmasphere, or alternatively under more disturbed magnetic conditions waves associated with detached plasma regions (Chappell 1974).

(*d*) *Pi 2 and magnetic bay observations*

Stuart (1972*a*, *b*, 1974, 1975*a*, *b*) and Stuart & Macintosh (1970, 1974), in an important series of papers, have analysed geomagnetic night-time activity at Halley Bay, St Anthony and Lerwick. Polarization studies have shown the following properties:

(1) The sense of polarization of Pi 2 events is mainly clockwise at Halley Bay and anticlockwise at Lerwick (Stuart & Macintosh 1970). This is consistent with the suggestion that these two observatories are mainly within the plasmasphere when Pi 2 events occur. It appears that in a given hemisphere the polarization sense changes at the plasmapause (Björnsson, Hillebrand & Voelker 1971; Orr 1975).

(2) In some Pi 2 events (Stuart 1975*b*) there are different times of arrival at the approximately conjugate locations of Halley Bay and St Anthony. The hodograms show even mode symmetry when the events are compared synchronously (after an initial settling time). However, when the hodograms are compared using first arrival of the disturbance as time reference odd mode symmetry is exhibited. These characteristics have been interpreted as due to eccentric location of the initiating disturbances which generates the Pi 2.

The high quality rubidium vapour magnetometers with flat frequency response, developed by the Institute of Geological Sciences (Stuart 1971), have enabled special features associated with Pi 2 events to be studied. Stuart (1972*b*) noticed that quite frequently the damped wavepacket characteristic of a Pi 2 event was not symmetrically disposed about the background field; there is often a rapid field movement associated with the beginning of a Pi 2 which makes the event appear to 'sit up' on the background field. This 'additional' magnetic field has been called the distension field and the pulsation event a dPi. The morphology of these events has been studied by Stuart & Macintosh (1974) and Stuart (1974, 1975*a*). The initial direction of the dPi rise changes with local time; at St Anthony and Halley Bay, in the dusk sector the direction is predominantly eastwards, in the pre-midnight sector northwards and westwards after geomagnetic midnight.

From a study of Pi 2 events detected on Explorer 45 and an array of ground stations in the Northern Hemisphere and at their conjugate station at Siple in Antarctica, Lanzerotti, Fukunishi, Maclennan & Cahill (1976) concluded that the u.l.f. magnetic power in the band 5–30 mHz is similar in the magnetosphere and on the ground and that the observations were odd mode waves.

(*e*) *Future work*

As part of the U.K. Programme for the International Magnetospheric Study 1976–8 a collaborative programme of observations and analysis of geomagnetic pulsations using ground-based magnetometers will be carried out by scientists from Imperial College, the University of York, British Antarctic Survey and the Institute of Geological Sciences. Magnetometers are being operated at Halley Bay, South Georgia in the South Atlantic and at St Anthony (in addition to the occupation of 15 other sites). The pair of stations Halley Bay and St Anthony, although they are approximately geomagnetically conjugate, have very different geographic latitudes and there are occasions when the local ionosphere of one observatory is in darkness while the other is in daylight and vice versa. It is proposed to compare the amplitude and travel time differences of pulsations between conjugate stations and relate the results to ionospheric conditions.

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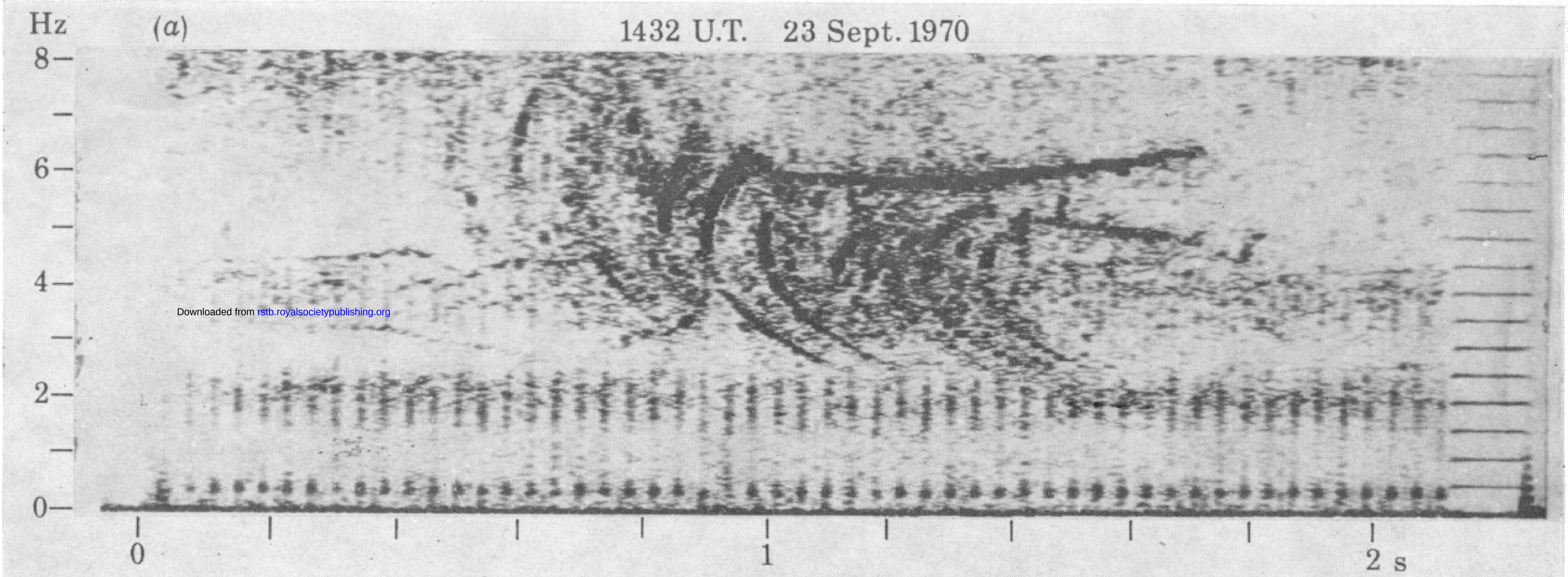
(a) 1432 U.T. 23 Sept. 1970

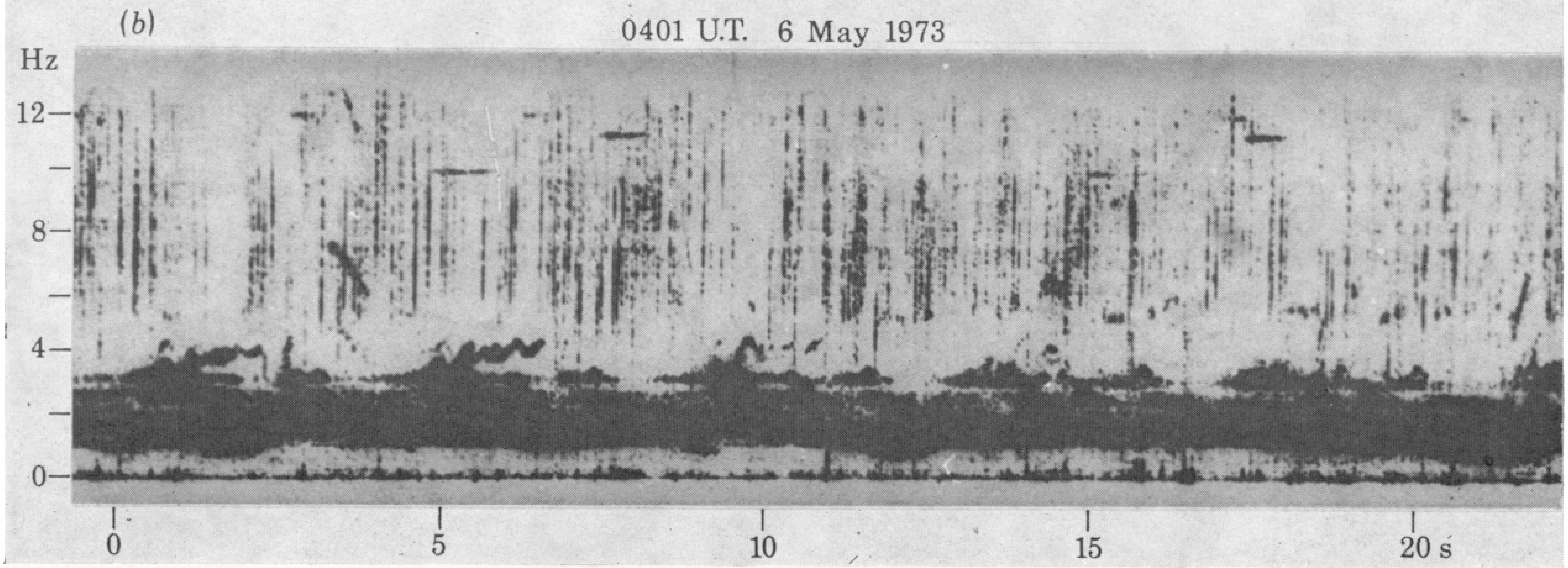
(b) 0401 U.T. 6 May 1973

Figure 4*a*. Spectrogram of whistlers observed at Halley Bay. Pronounced triggered emissions can be seen commencing at the upper frequency limit of two of the whistler components.

Figure 4*b*. Spectrogram of discrete v.l.f. emissions observed at Halley Bay. Constant frequency signals at 10.20 and 11.33 kHz originate from an Omega radio navigation transmitter.