THE ULF/VLF CORRELATOR EXPERIMENT AT HALLEY

H. Gough, D. Jones *and* K. H. Yearby*

British Antarctic Survey, Natural Environment Research Council, High Cross,
Madingley Road, Cambridge CB3 0ET, UK

Abstract. This paper describes the scientific objectives and first results of a new ULF/VLF project at Halley. It also outlines the experimental system and describes its installation during the 1985–86 relief operations. It illustrates how the project fits coherently into the ongoing VLF and geomagnetic observations at Halley. It reports some of the previous observations in this field and the suggested mechanisms for the relationship between the ULF (< 3 Hz) and VLF (0.5–10 kHz) waves and their interaction through the charged particles in the magnetosphere and in the ionosphere. The system extends the frequency range of magnetic variations recorded at Halley to cover the 'high' frequency Pc1/2 pulsations, and the relation of these pulsations to the plasmapause is discussed. Two examples of data recorded on the new system are presented, one a structured Pc1 event and the other a correlated ULF/VLF event identified from its cross-spectral phase.

1. Introduction

A novel experiment by the Space Plasma Physics Group of BAS was installed at Halley, Antarctica, during the 1985–86 relief operation. This new ULF/VLF project is designed to answer certain questions concerning the complex interaction of charged particles and VLF radio waves in the magnetosphere and the subsequent changes that occur in the ionosphere. Since the sensors are sensitive to magnetic variations in the frequency range 0.1–8 Hz, the frequency range of geomagnetic variations recorded and studied at Halley is extended to include the higher frequency Pc1/Pc2 magnetic pulsations. These measurements complement the data from the existing rubidium vapour magnetometer, which measures lower-frequency Pc2/Pc5 pulsations in the range 2–100 mHz and the data from the fluxgate magnetometer which measures geomagnetic variations with periods of 10 min and more ($f < 2$ mHz).

Over the years, many magnetospheric phenomena have been studied using ground-based observations, often as the result of an 'event' observed by one instrument at one location. In order to increase the understanding of magnetospheric structure and processes it is necessary to make observations on a larger spatial scale. This can be, and has been, done with an array of identical, or similar, instruments (e.g. Gough and [illegible]r, 1986). Alternatively, it is possible to take advantage of many measurements of different manifestations of related phenomena at one location. In the Antarctic the latter is the easier course to follow.

Observations have been made in the past which show that VLF and ELF radio waves in the frequency range 1–10 kHz are occasionally amplitude modulated at frequencies in the range 5 mHz–5 Hz (e.g. Sato and others, 1974; Willis and Davis 1976; Koons, 1977; Sato and Kokubun, 1980, 1981). This modulation is sometimes accompanied by coincident and similar ULF variations in the magnetic field (e.g. Sato, 1984). It is this relationship which is being investigated in greater detail using the new experiment at Halley.

At Halley, VLF radio waves have been recorded for more than a decade and numerous studies of whistler-mode waves have been performed. To pursue the investigation of a possible relation between temporal variations in the VLF waves with

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* Present address: Department of Physics, University of Sheffield, Sheffield S37 7RH.

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magnetic pulsations requires a ULF receiving system in addition to the existing VLF system. To reduce the amount of data recorded it was considered advantageous to endeavour to correlate the VLF and ULF variations in real time and to retain only those signals which showed significant correlation. It was fortunate that CRPE/CNET, Issy-les-Moulineaux, Paris offered to donate to BAS a set of magnetic coils and pre-amplifiers sensitive to variations in the 0.1–10 Hz range which had previously been used at Kerguelen and for conjugate measurements with the GEOS satellite (Perraut and others, 1978). The correlator/logger equipment and software have been developed in conjunction with BAS Common Services and are described in section 4.

2. Previous Work on Related VLF Waves and ULF Modulation

2.1. *VLF waves and short period 0.2–2 Hz pulsations*

The explanation put forward to explain the modulation of VLF waves (particularly at the higher frequencies ~ 1 Hz) and the simultaneous magnetic variations is illustrated in Fig. 1 and can be described as follows (Fraser-Smith and Helliwell, 1980). A whistler-mode VLF wave which is travelling away from the Earth along a geomagnetic field line, either as a result of a lightning discharge in the atmosphere or through direct man-made injection of the signal by a VLF transmitter, arrives near the Earth's magnetic equatorial plane and interacts strongly with energetic electrons through gyroresonance. In the gyroresonance interaction the injected wave amplitude may grow by 30 dB or more (Kennel and Petschek, 1966). In the process a significant number of resonant electrons which travel in the direction opposite to that of the wave are scattered into the loss cone of the pitch angle distribution, i.e. their pitch angles are reduced such as to cause their precipitation into the ionosphere. This has the effect of changing the ionospheric conductivity, and thus the ionospheric current, resulting in a variation in the magnetic field which can be detected on the ground. The amplified whistler-mode wave continues its journey towards the conjugate ionosphere. Part of the wave energy penetrates the ionosphere to be received on the ground, whereas some is reflected as a whistler mode wave travelling back along the geomagnetic field line. This reflected whistler-mode wave arrives back at the magnetic equatorial plane where it can once again undergo gyroresonance interaction with oppositely-travelling electrons. The process can continue with whistler-mode waves bouncing back and forth; each time that they are near the equatorial plane they cause electrons travelling in the opposite direction to be scattered into the loss cone.

The packets of energetic (~ 10 keV) electrons which are scattered into the loss cone proceed along the field lines from the equatorial plane and deposit themselves in the *D* and *E* regions of the ionosphere. Fig. 2 is a sketch showing the effect of the electrons in the ionosphere. The precipitating electrons produce numerous secondary electrons and the extra ionization in the ionosphere creates an enhancement of electrical conductivity in the volume of the precipitation region. In the presence of an electric field in the ionosphere, the periodic arrival of these electrons causes periodic changes in the current flowing in the ionosphere. These result in periodic changes in the geomagnetic field detectable below the ionosphere, at the surface of the Earth.

The periodicity with which the electrons arrive in the ionosphere depends on the periodicity with which they are scattered into the loss cone at the equatorial plane. This is determined by the whistler 'hop' time, the time taken for a whistler-mode wave to travel from one ionosphere to its magneticially conjugate point at the ionosphere

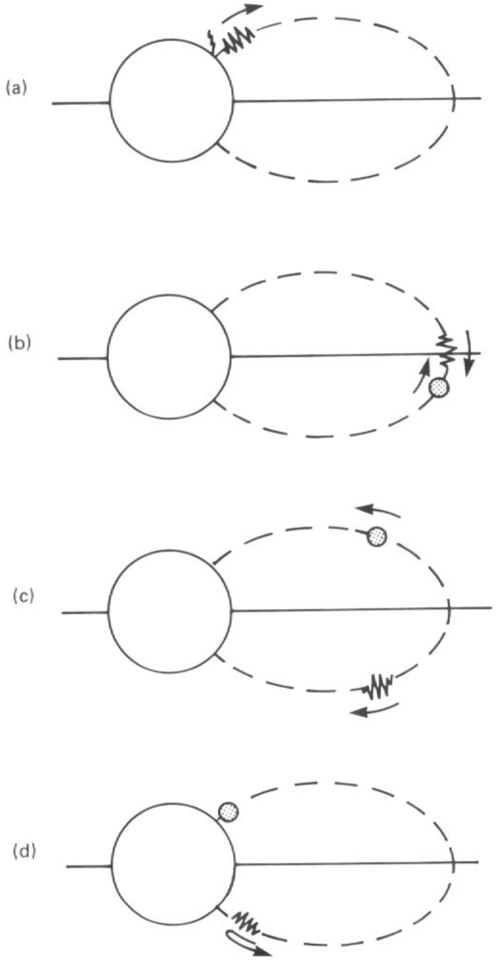

Fig. 1. An illustration of how ULF variations in the geomagnetic field can be produced by the interaction of VLF waves and charged particles in the magnetosphere. (a) A VLF wavepacket generated by lightning travels along the geomagnetic field line as a whistler-mode wave. (b) The VLF wavepacket interacts with oppositely moving electrons in the magnetosphere near the magnetic equatorial plane. (c) The modified packet of energetic particles travels towards one hemisphere whilst the VLF wave packet travels towards the other. (d) The arrival of the particles in the ionosphere causes changes in the geomagnetic field measured on the ground. Meanwhile, the VLF wave packet can be reflected from the conjugate ionosphere, back along the field line and the process is repeated.

in the other hemisphere. It is this whistler 'hop' time which determines the periodicity of the associated magnetic variations recorded on the ground.

2.2. *QP emissions and magnetic pulsations*

Another form of oscillatory type of VLF wave activity has been termed Quasi Periodic VLF emissions (Sato and others, 1974). The QP VLF emissions have a periodicity in the range 10–60 s, but mostly around 20 s. QP emissions have been classified into 2 types, one of which (type I) is associated with simultaneous Pc3/4

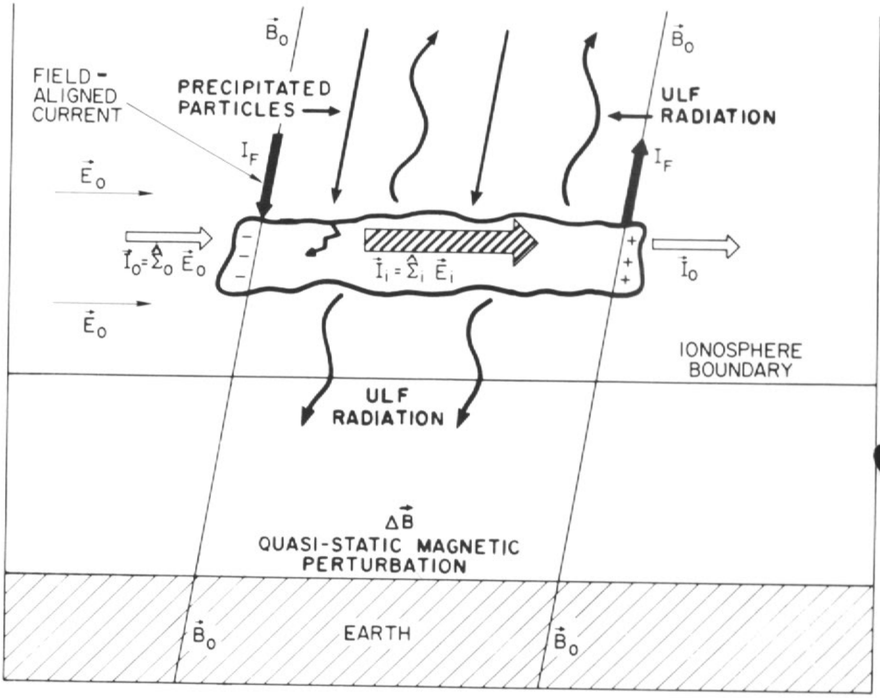

Fig. 2. The effect of energetic electrons arriving in the ionosphere. The extra ionization caused by the incident electrons increases the conductivity of the ionosphere (Σ_i) which, in the presence of an electric field in the ionosphere (E_0), changes the current flowing in the ionosphere (from I_0 to I_i) and alters the magnetic field on the ground (by ΔB). The periodic arrival of these electrons causes periodic changes in the ULF band in the geomagnetic field recorded on the ground (after Bell, 1976).

magnetic pulsations. Several observations have been made which correlate ionospheric conductivity changes as measured by riometers with Pc3/4 pulsations (Lanzerotti and others, 1978, 1985) and with substorm Pc2 pulsations (Lanzerotti and others, 1980). The other type of QP VLF emissions (type II) is not associated with any concomitant magnetic pulsations.

An example of type I QP emissions associated with a Pc3 wave is shown in Fig. 3. Fig. 3a shows the frequency-time spectra of VLF wave activity up to 1 kHz. The QP activity consists of rising frequency tones which occur with a repetition rate of about 20 s. The upper panel of Fig. 3b shows the envelope of the VLF emissions in a filtered band (bandwidth 25 Hz) centred on 0.7 kHz, together with the H component of magnetic pulsations; the middle panel illustrates power spectra of the time-series shown in the upper panel showing both to have a peak near 50 mHz (a 20 s periodicity); the lower panel displays the coherency spectrum between the two time-series again showing a peak near 20 s.

The mechanism suggested for this process is illustrated in Fig. 4. In Fig. 4a there is an existing source of ELF/VLF emissions (chorus and/or hiss) near the equatorial plane, with the emissions propagating along the geomagnetic field lines towards the Earth. The emission (source) mechanism is then modified by a magneto-hydrodynamic fast-mode wave which propagates radially toward the Earth. The ELF/VLF emissions are modulated by the compressional component of the hydromagnetic wave which is modifying the electron gyroresonance instability (Kennel and Petschek, 1966). The

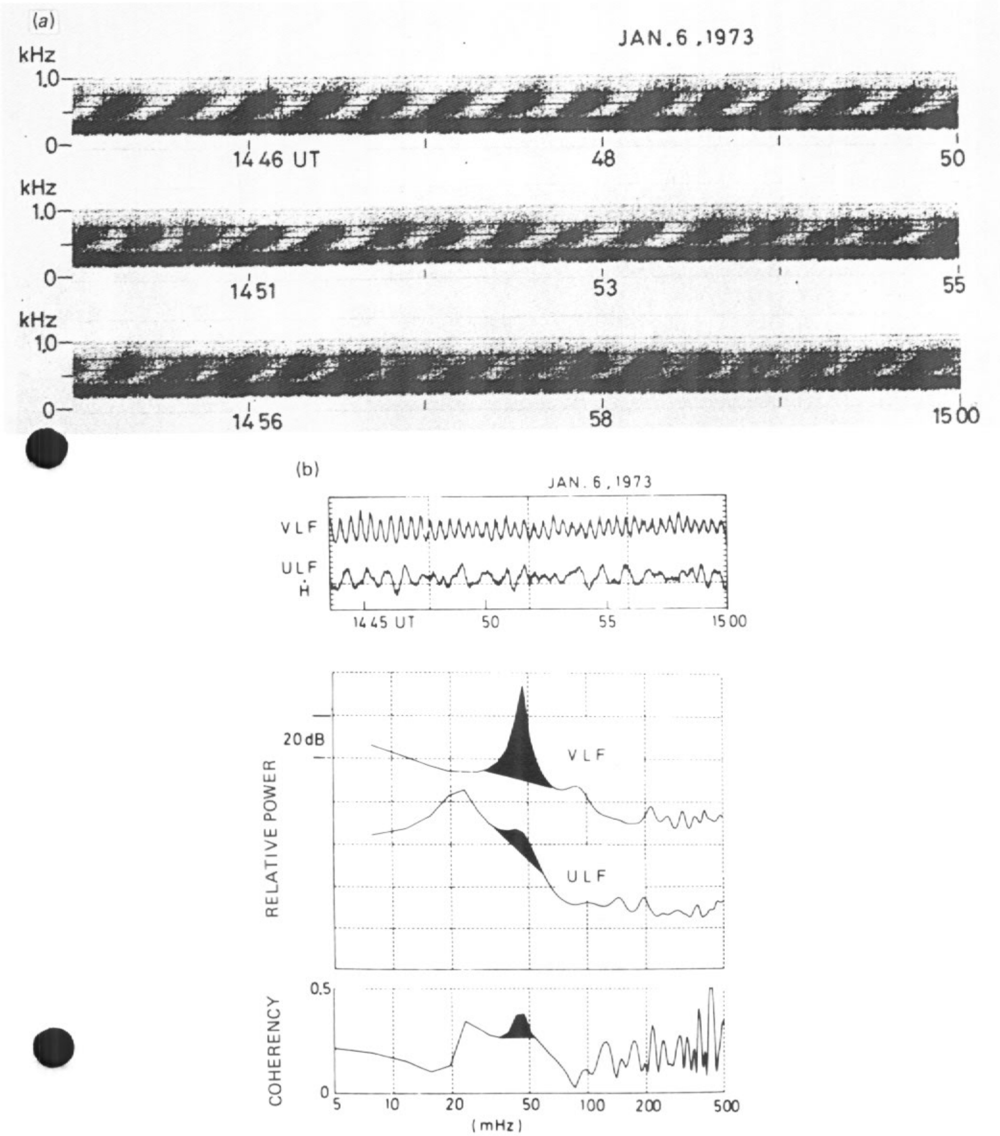

Fig. 3. QP emissions and pulsations. (a) Frequency-time spectra of QP emissions in the VLF band up to 1 kHz observed at Syowa, Antarctica. (b) Top panel: intensity records of VLF emissions in a frequency band centred on 0.7 kHz and the H component magnetic variations, both from the same time as (a). Lower panels: relative power spectra and coherency spectrum of the time series shown in the upper panels. (Sato and Kokubun, 1981.)

periodic increase and decrease in intensity of VLF/ELF emission is brought about by the periodic increase and decrease of the magnetic field strength (Coroniti and Kennel, 1970). Between times T_1 and T_2 in Fig. 4a, the radially travelling wave will cause variations in intensification of VLF/ELF emissions over a range of distances from the Earth. As the frequency of the VLF emissions depends on the equatorial

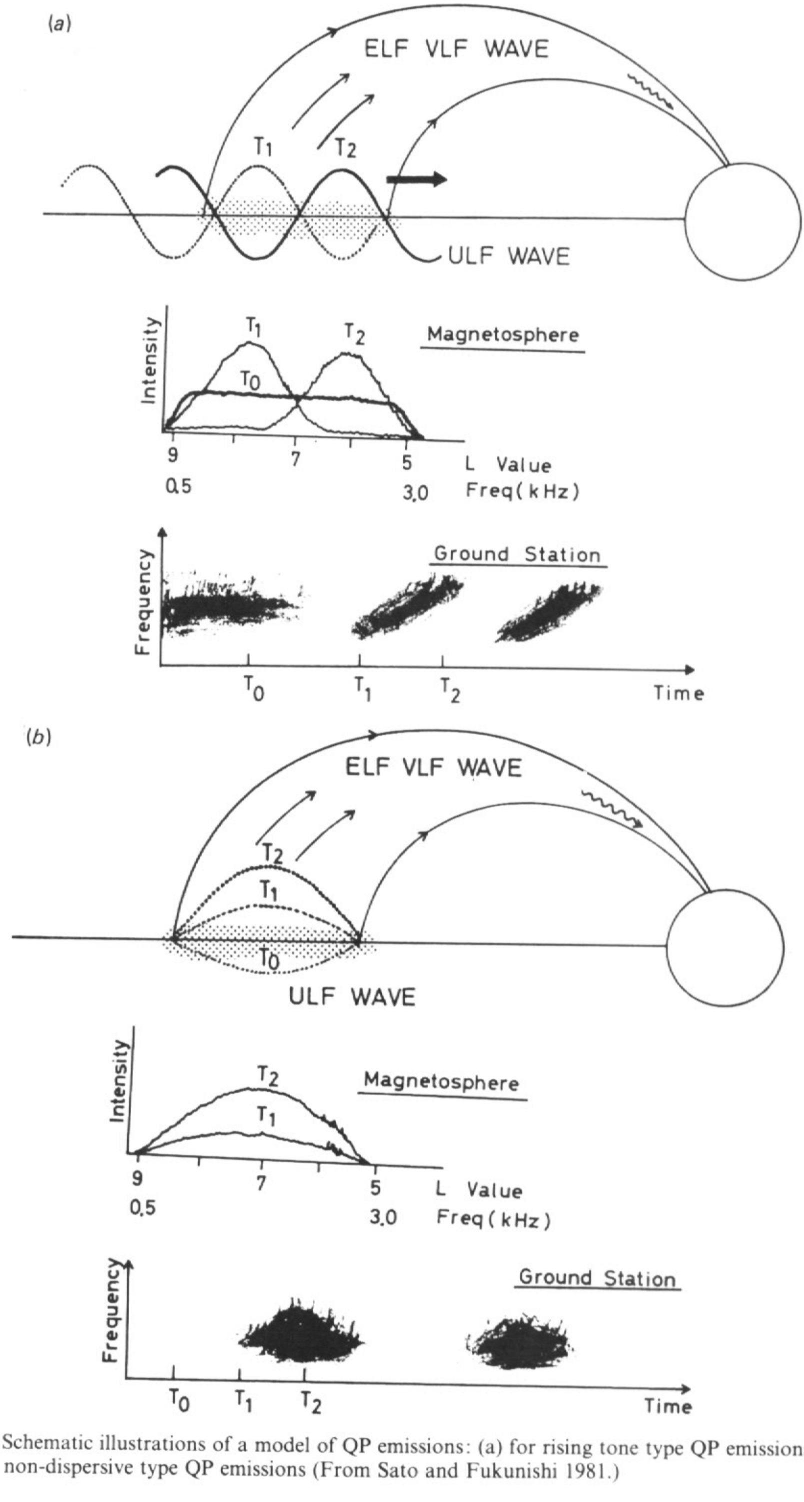

Fig. 4. Schematic illustrations of a model of QP emissions: (a) for rising tone type QP emissions; (b) for non-dispersive type QP emissions (From Sato and Fukunishi 1981.)

cyclotron frequency which in turn depends on the geocentric distance, the travelling ULF wave will alter the intensity of the emission over an increasing frequency as it travels towards the Earth (see lower panel of Fig. 4a).

In Fig. 4b the principle of the modification mechanism is the same as for Fig. 4a except that the modifying hydromagnetic wave is a longer period Pc4 standing wave which also has a significant compressional component. Intensity fluctuations thus occur simultaneously over a range of geocentric distances, thus modifying all frequencies nearly simultaneously as illustrated in the lower panel of Fig. 4b.

2.3. *Impulsive particle precipitation and ULF waves*

Ground based riometers, photometers and balloon-borne X-ray detectors have all observed the impulsive arrival of energetic electrons in the ionosphere (e.g. Engebretson and others, 1983; Lanzerotti and Rosenberg, 1983). These events usually occur in conjunction with whistlers (e.g. Rycroft, 1973). The energetic electrons are thought to come from the belts of trapped particles in the magnetosphere (Voss and others, 1984). The impulsive arrival of the energetic electrons is accompanied by concurrent magnetic field variations produced by the changes in ionospheric current systems. The change in the particle distribution in the magnetosphere is also likely to affect any VLF/ELF emissions. The impulsive variations have a short (~ 2–4 s) onset time and a ~ 5–10 s decay time. The decay times are consistent with ionospheric 'response times' for the recombination of ions and electrons in the ionosphere at ~ 90–100 km (Lanzerotti and Rosenberg, 1983). This response time is an important parameter to consider for the associated VLF and short period pulsations.

3. Pc1 PULSATIONS AND THE PLASMAPAUSE

Pc1 pulsations are short period hydromagnetic waves (0.2–2 Hz). Their wavelength is small compared with their path lengths in the magnetosphere (unlike Pc3/5 pulsations) and they have been termed 'hydromagnetic whistlers'. Pc1 pulsations often appear as structured events in which a hydromagnetic wave packet containing many wavelengths travels along a geomagnetic flux tube 'bouncing' alternately from one hemisphere to the other (Fig. 5). It is generally accepted that Pc1 pulsations are ion cyclotron waves generated in the equatorial region of the magnetosphere by the proton gyroresonance instability (Fraser and others, 1984). The group velocity, v_g, of the wave packet is close to the Alfvén velocity; this suggests that the 'bounce' time [illegible] analogous to the periodicity of Pc3/5 pulsations whose wavelengths are comparable with the dimensions of the magnetosphere. Thus it will be interesting to compare the bounce time of Pc1 waves detected by the new ULF coils at Halley with the periodicity of Pc3/5 waves detected by the existing rubidium vapour magnetometer. These measurements could give an indication of the position of the plasmapause relative to the position of the station, which could then be compared with whistler derived plasmapause positions obtained from AVDAS (Advanced VLF Data Analysis System) (Smith and Yearby, 1987) and ionospheric signatures of the plasmapause derived from the Advanced Ionospheric Sounder (AIS) at Halley (Smith and others, 1987).

Pc1 pulsations are thought to occur most frequently at two different times – during substorm commencements and several days after substorm onset (Roth and Orr, 1975). During a substorm the ring current builds up outside the plasmasphere. After a substorm the plasmasphere expands and the ring current diffuses radially. After some time, possibly over several days, the ring current particles mix with the colder

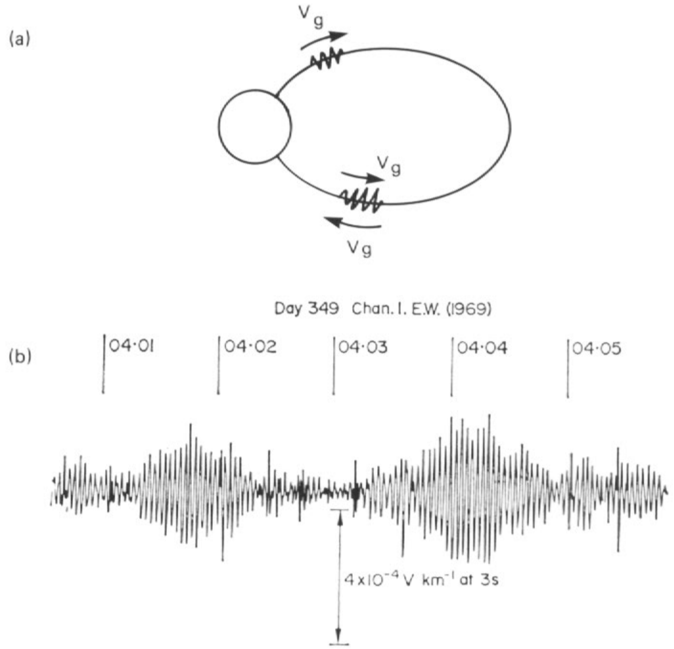

Fig. 5. (a) A Pc1 wave packet bouncing from hemisphere to hemisphere in the magnetosphere, with a group velocity of v_g, and (b) a Pc1 event of approximately 3 s period and 2 min bounce period recorded at South Uist, UK, on 15 December 1969 (after Orr, 1973).

plasmaspheric plasma and excite proton cyclotron resonance waves which manifest themselves as the Pc1 pulsations.

There has also been the suggestion (Reid, 1976) of an ionospheric source for Pi1 and Pc1 (Pi1 are impulsive type Pc1); the changes in ionospheric currents caused by precipitating electrons could themselves be a source which produces hydromagnetic Pc1 waves which propagate into the magnetosphere. In this case changes in ionospheric currents may provide the initial stimulus for Pc1 pulsation events.

4. RALF – The ULF/VLF Correlator and Data Logger

The Real-time Antarctic Logger Facility (RALF) has been developed and commissioned by the Space Plasma Physics Group and Common Services to form the second generation of standard computerized BAS loggers for use in the Antarctic. The first generation of loggers passively sampled data channels and recorded these data directly on to magnetic tape. RALF has software for analysing in-stream data in real time and then deciding automatically whether to record the data or not. The benefits of such a system are: (i) Magnetic tape usage is greatly reduced. This reduces the cost, not only of magnetic tapes but also of their transportation and storage. (ii) The time spent studying large amounts of data in an attempt to find events of scientific interest is minimized.

These features are particularly important for the study of ULF/VLF relations, where events are unpredictable and where the sampling rates required (20 Hz) would yield too many tapes to be routinely analysed by the available manpower in the year between relief visits to Halley.

The hardware of RALF is based on a standard 'BAS-micro' computer, a computer system based on the 6809 processor and designed by BAS for data-logging applications. Extra hardware was developed to condition the input signals by the logger. The logger inputs are the signals from three orthogonal ULF sensors (X, Y, Z) and the wide-band signals from the VLF receiver. The broad-band VLF signal is split into three amplitude-envelope signals by three analogue band-pass filters (frequency bands 0.5–1.5, 2.5–3.5, and 5–7 kHz) whose outputs are rectified and integrated. The data are recorded in digital form on standard nine-track computer tapes (see Fig. 6).

The 20 Hz sampled data from the six input channels are stored in buffers which hold 10 s of data (1200 data points/buffer). There are usually between six and nine such buffers in operation at any given time resulting in 1–1.5 min of data stored in the memory of RALF. Whilst one buffer is being filled, previously filled buffers are being analysed for peak values in the signal amplitude and for the degree of cross-correlation between the nine pairs of ULF and VLF channels. The VLF data are also digitally filtered and 'resampled' at 1 Hz to produce a 'low speed' VLF data stream which, together with the peak values of the signal amplitudes and cross-[illegible]relations, is always recorded on to the tape as background information. This will allow day to day variations in the wave activity to be examined. In addition, the 'high speed' (20 Hz sampled) data are automatically recorded on to the tape, either when one of the signal peak-to-peak amplitudes exceeds a set threshold or when the peak value of a cross correlation between a ULF channel and a VLF channel exceeds a set threshold.

When high-speed recording is initiated, the data recorded on the tape will start with the earliest data held in a buffer in the memory, giving 1–1.5 min of history before the threshold was exceeded. When all of the amplitude peaks or cross-correlations fall below their thresholds, recording will revert to the low-speed data-recording mode but only after a set period of time, approximately 5 min, has elapsed. In continuous low-speed recording mode, a tape will last for about 30 days, while in continuous high-speed recording mode it will last for about 36 h.

The setting of the thresholds is best done by the operator in the field who can balance the proportion of time in which 'high-speed' recording is carried out, and thus tape usage, against the level required to record the events of interest. Similarly, it is possible for the operator to alter the pre-set time taken for the logger to revert to low-speed recording mode after the end of an event which triggered high-speed

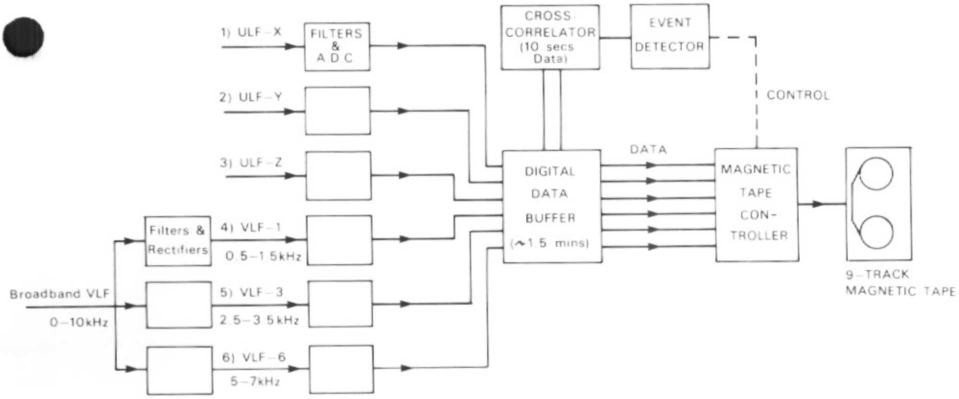

Fig. 6. Block diagram of the ULF/VLF correlator-logger.

recording. In addition the operator can override the threshold levels and issue a direct command to start or stop high speed recording or pre-set start and stop times up to 24 h in advance should it be necessary.

5. Installation of the ULF/VLF Experiment at Halley

The ULF/VLF equipment, including the ULF sensors and the RALF logger, was packed for shipment to the Antarctic in September 1985. At the same time a new caboose was shipped to Halley to house the existing VLF equipment (including the AVDAS) as well as the new ULF/VLF equipment. The RRS *Bransfield* arrived at Halley, Antarctica on 23 December 1985 and the VLF and ULF/VLF equipment was installed from 26 December, after the initial relief operations. The ULF sensors were deployed approximately 100 m to the west of the new VLF caboose. A steel rope catenary was run out to approximately 100 m from the caboose to carry the cables to the sensors. The sensors were placed approximately 10 m to the north, west and south of the end of the steel wire catenary. Rope catenaries were used to carry the cables the final distance to the individual sensors to avoid magnetic effects from the steel wires. Fig. 7 is a plan view of the arrangement of the cabooses and sensors.

Enclosures for the sensors were placed in holes made in the snow about 0.75 m deep to reduce the effects of wind vibration which would cause the sensors to move in the Earth's magnetic field and generate false signals. The enclosures for the X (N–S) and Y (E–W) sensors were aligned with a compass and spirit level, which was also used to set the Z (vertical) sensor. The logger equipment and the sensors were first switched on and tested on 31 December 1985.

At switch-on, the equipment and software performed as expected. A number of minor improvements and modifications were made both to the hardware and to the logging and correlation software as a result of experience during the first month of operation. Some 11 tapes were recorded during January 1986 and these were either brought out by the RRS *Bransfield* or flown out via Rothera base. They are in the process of being analysed (using the NERC Computing Services VAX 8600 computer at BGS Keyworth). A small amount of data has also been sent back from Halley via the satellite link (Jones, 1984). Software is under development which will be used to process the complete year's data which will be returned after future relief operations.

6. Preliminary Observations and Results

In this section we show some of the data collected during January 1986, the f[illegible] month of operation of the logger. Amongst the first data to be analysed were discovered approximately eighteen Pc1 events. Fig. 8 shows a spectrogram of one such event recorded on the X component sensor on 4 January 1986. Throughout the interval in the diagram there is continuous wave activity between approximately 0.3–0.4 Hz but, in addition, from approximately 16.45 to 17.15 UT, there is a structured Pc1 event at just under 1 Hz. The 'structure' appears as evenly spaced rising tones which indicate individual wave packets bouncing from hemisphere to hemisphere as discussed in section 3. The bounce time is approximately 2 min which would suggest, from hydromagnetic Alfvén wave propagation times, that the field line along which the Pc1 wave packet travelled is inside the plasmasphere as the approximate equatorial plasma number density required for this propagation time is 300 cm^{-3}. This structured event is followed from 17.30 to 17.40 by a 'monochromatic' emission at 0.8 Hz.

An investigation has been performed on the polarization of the horizontal wave

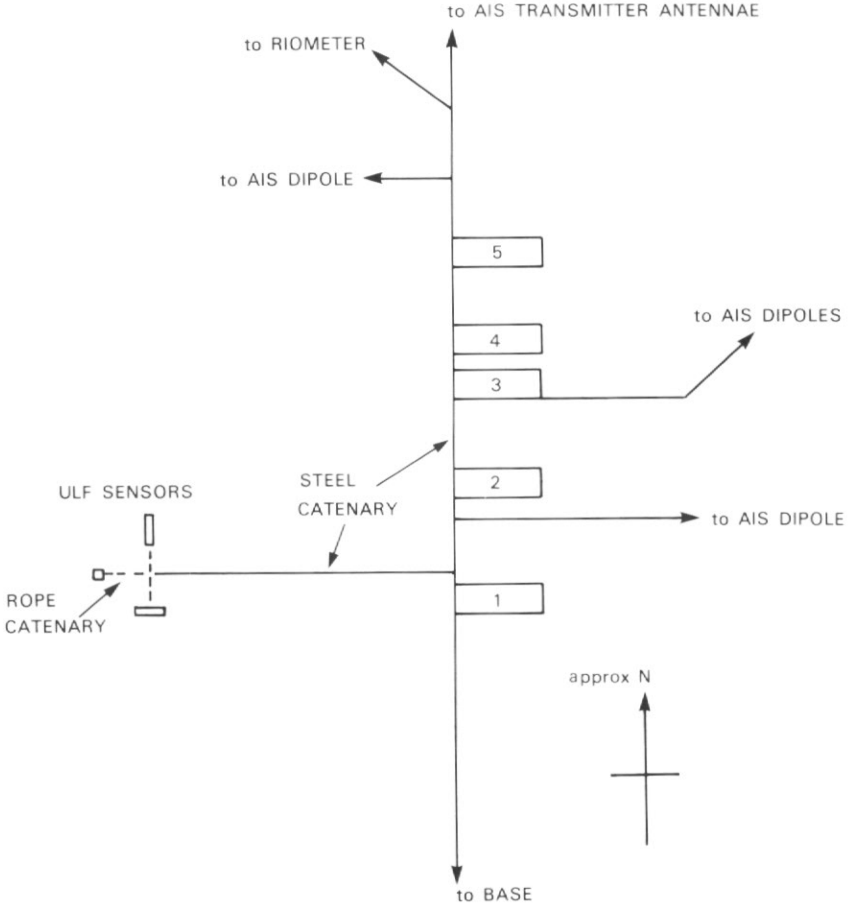

Fig. 7. Approximate position of the ULF sensors in relation to the other geospace experiments at Halley. The numbered cabooses are 1, VLF/AVDAS; 2, AIS generator; 3, AIS transmitter; 4, AIS workshop; 5, AIS office.

[illegible]ld of this Pc1 and the seventeen other Pc1 pulsations recorded during January 1986. In about 12 of the 18 events, where there is a reasonably clear polarization evident, the horizontal wave field is either linear or right-circularly polarized. In the example shown in Fig. 8 the rising tone structure from 16.45 to 17.15 UT is right circular polarized whereas the monochromatic emission which follows is linearly polarized with the major axis at 45° to the X and Y components. Fraser and others (1984) have used the orientation of the major axis of the polarization ellipse as an indicator of the direction of propagation of the Pc1 wave in the F2 region ionospheric wave guide. However, two or more stations are required for this method to be used to determine reliably the secondary ionospheric source at the foot of the field line (the magnetospheric exit point).

Comparisons are also being made with data from other instruments at Halley – AVDAS, AIS, riometer, and magnetometers. More detailed studies involving such comparisons will have to await the return of further data from the Antarctic.

The correlations between the three ULF components and the amplitude modulation of VLF waves in three frequency bands, all recorded by RALF during January 1986, have been extensively examined. Computer programs using cross-spectral amplitude and phase analysis routines from the NAG library available on the VAX 8600 have been developed for the RALF data. These routines have been applied to the data from January 1986. It has been found that the cross-spectral amplitude does not seem to be as good a method for determining intervals of related ULF and VLF activity as is the cross-spectral phase. The cross-spectral phase showed periods of correlated ULF and VLF activity appearing as periods of constant cross-spectral phase in frequency-time spectrograms. This technique has also been used in the past for identifying low-amplitude polarized waves on spacecraft (Jones and others, 1983). Fig. 9 shows an example of a period of constant cross-spectral phase between 0.5 and 1 Hz between the ULF X component and the VLF 6 kHz channel recorded from 3.30 to 12.30 UT on 12 January 1986. It would seem that there is evidence of a relationship between ULF and VLF waves. In particular, there seems to be a tendency for ULF waves of frequency 0.5–1.0 Hz to be correlated with oscillations at the same frequency in the amplitude of VLF waves in a frequency band centred at ~ 6 kHz. In the absence of recordings of the broad-band VLF signals (0–10 kHz), which are to be returned from the Antarctic in the near future, it is not possible at this stage to identify the precise mechanism for this correlation.

7. SUMMARY

The new ULF/VLF system has been operating at Halley since January 1986. The data sets already received indicate that the system is capable of recording the events for which it was designed. Further analysis of these and other data sets should yield a better insight into the complex relation between ULF and VLF waves, their interaction with the energetic and background magnetospheric charged particles, and their influence on the ionosphere.

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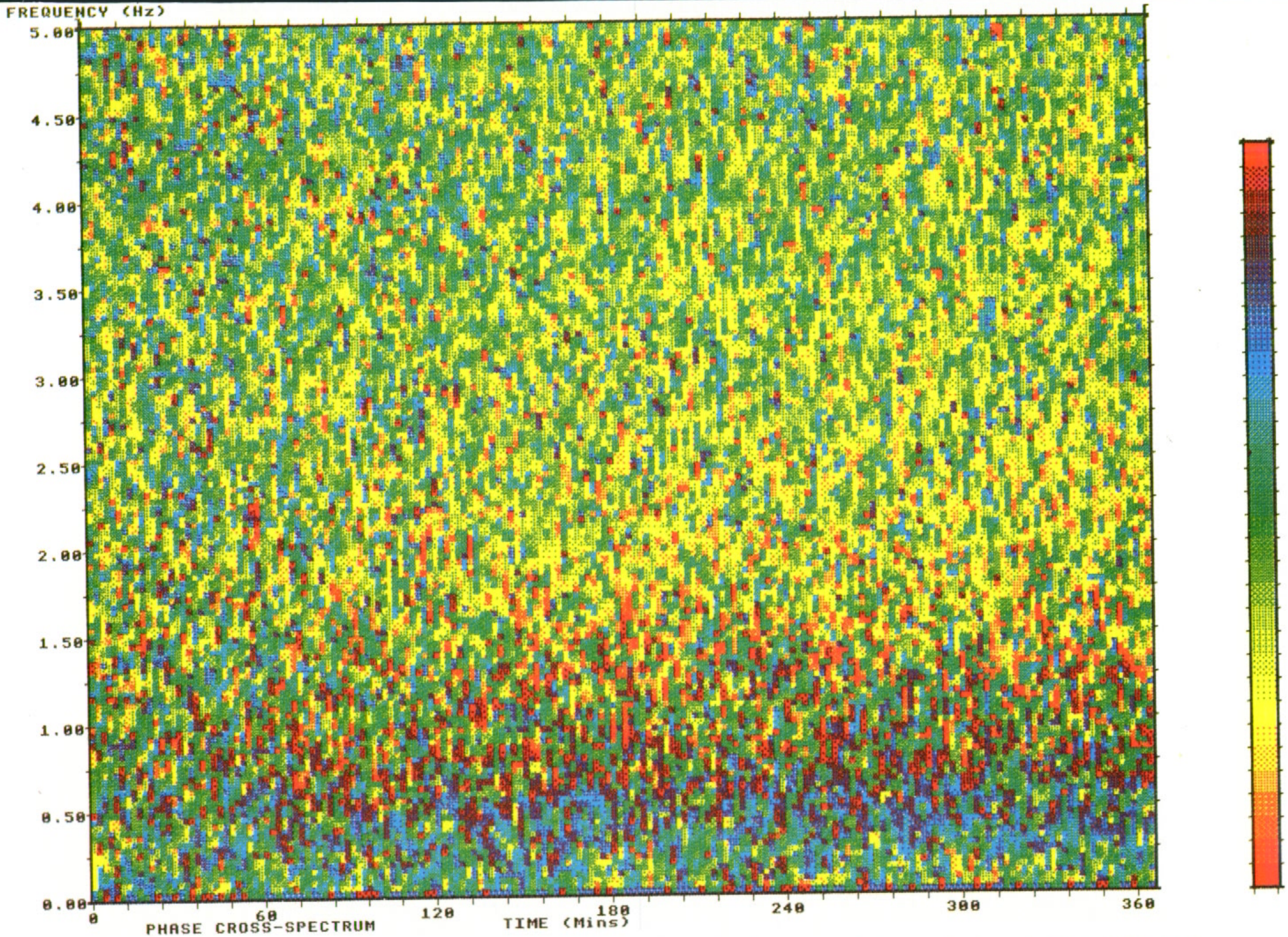

Fig. 9. Frequency-time plot of the cross-spectral phase between the ULF X sensor and the amplitude modulation of the VLF 6 kHz band pass signal recorded on 12 January 1986. There is relatively constant cross-spectral phase near 1 Hz throughout the interval.

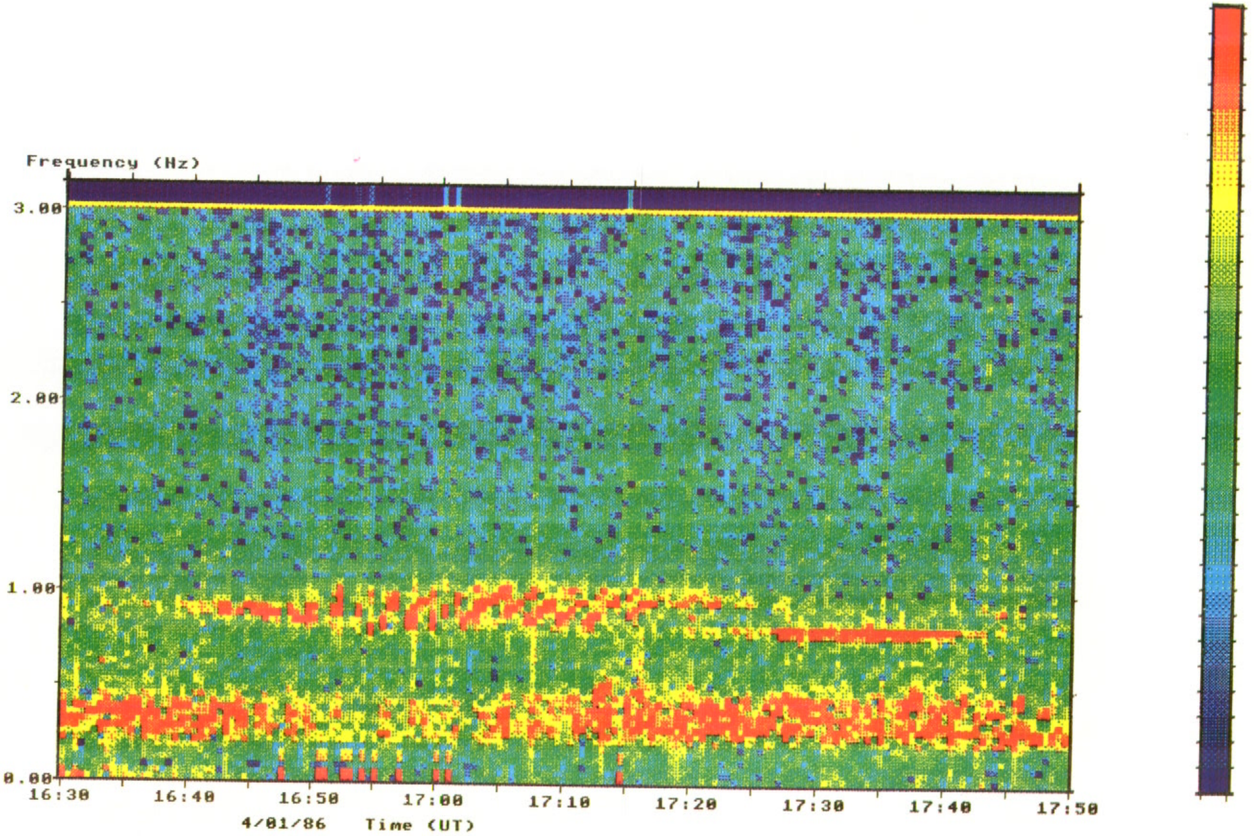

Fig. 8. Frequency-time plot of a structured Pc1 event recorded on the X (N-S) component sensor on 4 January 1986; for description see text.

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