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Periodic and quasiperiodic ELF/VLF emissions observed by an array of Antarctic stations

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Abstract. This paper describes amplitude modulations in the frequency range 0–500 mHz of ELF/VLF (0.5–4.0 kHz) radio wave power recorded throughout 1993 and 1995 at Halley and South Pole stations, Antarctica, which lie in approximately the same magnetic meridian and at geomagnetic latitudes (Λ) of 61° and 74°, respectively. Data from the intermediate automatic geophysical observatories P2 and P3 (Λ = 70° and 72°, respectively) were also analyzed where available. In agreement with earlier work, spectrograms have revealed the frequent daytime (typically 0700–1700 MLT) occurrence of modulations lying almost entirely within the two period ranges: 10–60 s and 4–6 s. The first range corresponds to quasiperiodic (QP) emissions, while the latter is typical of the two-hop whistler mode echo period in the plasmatrough, and the events are termed periodic emissions (PEs). QP occurrence rates higher than some earlier studies (335 station-days out of 667 examined) may be attributable to the sensitive spectral analysis technique. The type I QPs (i.e., those correlated with geomagnetic pulsations observed at South Pole and/or P2/P3) were consistent with an upstream wave driver, controlled by the IMF cone angle. Type II QPs (uncorrelated with magnetic pulsations) were always accompanied by PEs, suggesting a link between the two, reinforced by a frequently observed steady increase in period in both phenomena, especially during the morning, possibly associated with increasing densities due to upward flow of photoionized plasma from the ionosphere after dawn. Here we propose that type II QPs are driven by field line resonant ULF waves which in turn are generated by field-aligned currents arising from PE induced electron precipitation.

1. Introduction

This paper concerns periodic and quasiperiodic amplitude variations in the frequency range 1–500 mHz of magnetospherically generated ELF/VLF radio emissions, as observed at high-latitude ground stations, together with their relationship to geomagnetic pulsations of similar period. It uses the high-quality data now becoming available from the British and U.S. networks of Automatic Geophysical Observatories in Antarctica, together with a processing and display technique which permits variations over the whole frequency range to be viewed on the same color spectrogram.

Amplitude-modulated VLF/ELF emissions observed on the ground were classified by *Helliwell* [1965], who noted various types of periodic emissions (PEs), which usually had periods of a few seconds and were often associated with whistler mode waves echoing along geomagnetically field-aligned paths between opposite hemispheres. By contrast, quasiperiodic (QP) emissions consisted of repeated noise bursts of longer (tens of seconds) and more irregular period. QP emissions were further classified into type I and type II by *Sato et al.* [1974] on the basis of whether or not they were well correlated with coincident geomagnetic pulsations. Other emissions types have been reported which show a degree of quasiperiodicity of somewhat shorter period, such as "hisslers" [*Ungstrup and Carpenter*, 1974] and "pulsing hiss" [*Ward et al.*, 1982]. These, however, unlike the QP emissions discussed here, are largely a nighttime phenomenon associated with substorms and pulsating aurora respectively. The subject has recently been reviewed by *Sazhin and Hayakawa* [1994].

In this paper we display these modulations by means of color spectrograms, produced by Fourier transformation of the time series representing the amplitude envelopes of each of a number of relatively wide ELF/VLF frequency bands. This is an effective technique for detecting the presence of periodicities which may other-

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wise be masked by more dominant but aperiodic fluctuations. Because we difference the data before FFT processing (which "whitens" the spectrum, effectively compensating for the $\sim 1/f$ dependence), we are able to display simultaneous variations at different frequencies across the entire 1–500 mHz range, without the need for background subtraction or other modifications of the resulting spectrum. The results reported here are based upon color spectrograms produced routinely from data collected in Antarctica during 1993 and 1995. Where it is necessary to distinguish between the wave frequency of the VLF/ELF emission itself, and the frequency of any periodicity observed in its amplitude, the engineering terms "carrier frequency" and "modulation frequency" (respectively) will be used.

2. Experimental Configuration

The data presented in this paper are from four Antarctic stations. Two are the manned stations of Halley (HB) and South Pole (SP). The others are the unmanned Automatic Geophysical Observatories P2 and P3 [*Rosenberg and Doolittle*, 1994; *Engebretson et al.*, 1997], two of the six U.S. AGOs currently deployed on the Antarctic ice sheet. The locations of the stations are shown in Figure 1 and their coordinates in Table 1. Halley, South Pole and P2 lie roughly in the same magnetic meridian, with local magnetic noon occurring at about 1500 UT; P3 is somewhat to the east (local magnetic noon ~1400 UT). Both manned and unmanned stations have an abundance of instrumentation, but here we will be concerned only with the magnetometers and VLF/ELF receivers.

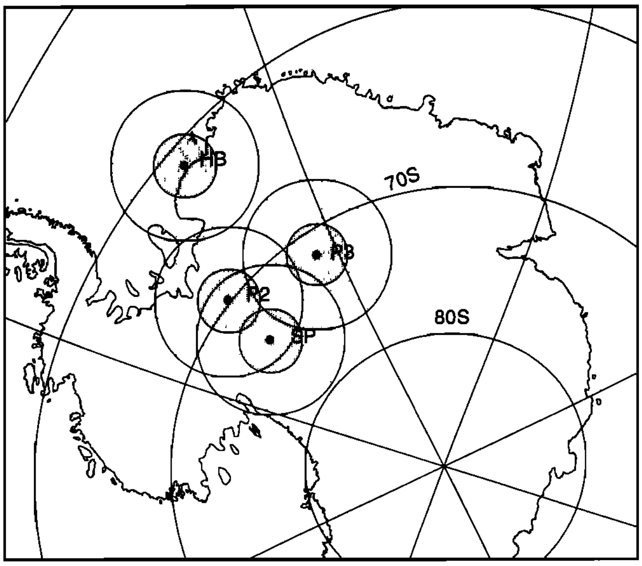

Figure 1. Map of Antarctica, showing the observatories from which data were used in this study: Halley (HB); AGO (P2), AGO (P3); South Pole (SP). Circles of radius 250 and 600 km, centered on each site, are a schematic representation of the typical fields of view of the magnetometer and VLF receiver, respectively.

Table 1. Geographic Coordinates and Invariant Geomagnetic Latitudes (Λ) of the Antarctic Stations Providing Data for This Study

Station	Latitude	Longitude	Λ
HB	75.5°S	26.7°W	61°S
P2	85.7°S	46.4°W	70°S
P3	82.8°S	28.6°E	72°S
SP	90.0°S	—	74°S

2.1. South Pole

The magnetometer is the University of New Hampshire search coil instrument [*Taylor et al.,* 1975] which measures the rate of change of the ambient geomagnetic field at a rate of 10 samples per second. We generally plot the northward (X) component of this quantity, X_{BB}. The VLF/ELF data come from the Stanford University receiver, which has three channels (VLF1: 0.5–1.0 kHz; VLF2: 1.0–2.0 kHz; and VLF3: 2.0–4.0 kHz) with center frequencies 0.75, 1.5, and 3.0 kHz [*Shafer et al.,* 1994]. In 1993 the VLF1 channel was missing or intermittent due to a hardware fault. The VLF channel amplitudes were sampled once per second and recorded along with the magnetometer data by the University of Maryland data-logging system.

2.2. AGOs P2 and P3

The Stanford VLF receivers and associated instrumentation were essentially the same as at South Pole. However, there was no VLF1 channel, and two orthogonal components of the VLF2 channel (north–south and east–west) were each sampled just once every 2 s. For the purposes of this paper we use only the latter, VLF2EW. The search coil magnetometer was provided by Tohoku University, Japan [*Fukunishi et al.,* 1994].

2.3. Halley

The instrumentation at Halley has been described by *Dudeney et al.* [1995, 1997]. The magnetometer is a three-axis fluxgate, with each axis sampled once per second. We plot the horizontal (northward) component of the field, denoted B_{H}. VLF data are from the VELOX (VLF/ELF logger experiment) instrument [*Smith,* 1995] which has eight channels, though here we are concerned only with the lower five of these which have center frequencies (and bandwidths) in kHz of 0.5 (0.5), 1.0 (1.0), 1.5 (1.0), 2.0 (1.0), and 3.0 (1.0). The frequency ranges covered by the 3.0 and 1.5 kHz channels are directly comparable with the South Pole, P2, and P3 VLF3 and VLF2 channels. The South Pole VLF1 channel corresponds to the upper half of the Halley 0.5-kHz channel and the lower half of the Halley 1.0-kHz channel. In this paper we use the VELOX amplitude data which are sampled and stored once per second. We also had available for comparison data from the Halley broadband VLF goniometer receiver [*Smith and Nunn,* 1998].

3. Data Analysis

The Halley and South Pole data for every day in 1993 and 1995 have been scanned for PE and QP VLF/ELF events; we have also examined all the data available from P2 in 1993 (days 1–151) and P3 in 1995 (days 26-186). The data presentation format which most clearly shows VLF/ELF modulation periodicity is the colour spectrographic matrix format illustrated for April 12, 1993, in Plate 1, which displays the Fourier transform of the differenced time series data. Each column represents data from a different station, whereas rows correspond to different channels, with the magnetometer data at the bottom. Within each panel the power (coded by color) of every spectral component is plotted vertically as a function of frequency (modulation frequency for the VLF/ELF channels) and horizontally as a function of time (universal time). The frequency scale extends to 500 mHz, the Nyquist frequency for data sampled at a 1-Hz rate. The data extend only to 250 mHz for the 0.5-Hz sampled P2 and P3 VLF2 data.

In principle, it is possible for spurious traces to arise from the aliasing of strong out-of-band modulation frequencies. Because of the way the signals are filtered and processed, this will be a potential problem only near the Nyquist frequency, with modulation frequency f producing an alias at $(2f_{\mathrm{Nyquist}} - f)$. In the case of the 0–500 mHz spectrograms from SP and HB, such spurious signals are rarely seen in practice, and their absence may be confirmed by reference to the broadband data; we are confident that there are none in the figures presented here. In the 0–250 mHz P2/P3 spectrograms we sometimes do see weak aliases of frequencies just above 250 mHz (where there is often significant modulation power). Such cases are apparent when comparing the spectrograms with corresponding 0–500 mHz plots from the other stations. There is only one example in the figures presented here, in Plate 2 between 0800 UT and 1200 UT.

In the presentation format of Plate 1, concentration of spectral power into horizontal or approximately horizontal bands and lines represents Pc pulsations when seen in the magnetometer data, and PE or QP emissions when seen in the VLF/ELF channels. In order to show the details of the correlations between different channels or different stations, we may alternatively represent the spectra as line plots (e.g., Figure 2).

4. Characteristic Features

4.1. Modulation Frequencies and Bandwidths

Modulation power at ELF/VLF carrier frequencies is typically found to be observed in two nonoverlapping frequency ranges: (1) 10–100 mHz and (2) around 200–300 mHz. These correspond, in Helliwell's [1965] notation, to QP and periodic emissions respectively, and we will use this terminology here. They often occur together, as seen in Plate 1 at all three stations. Fig-

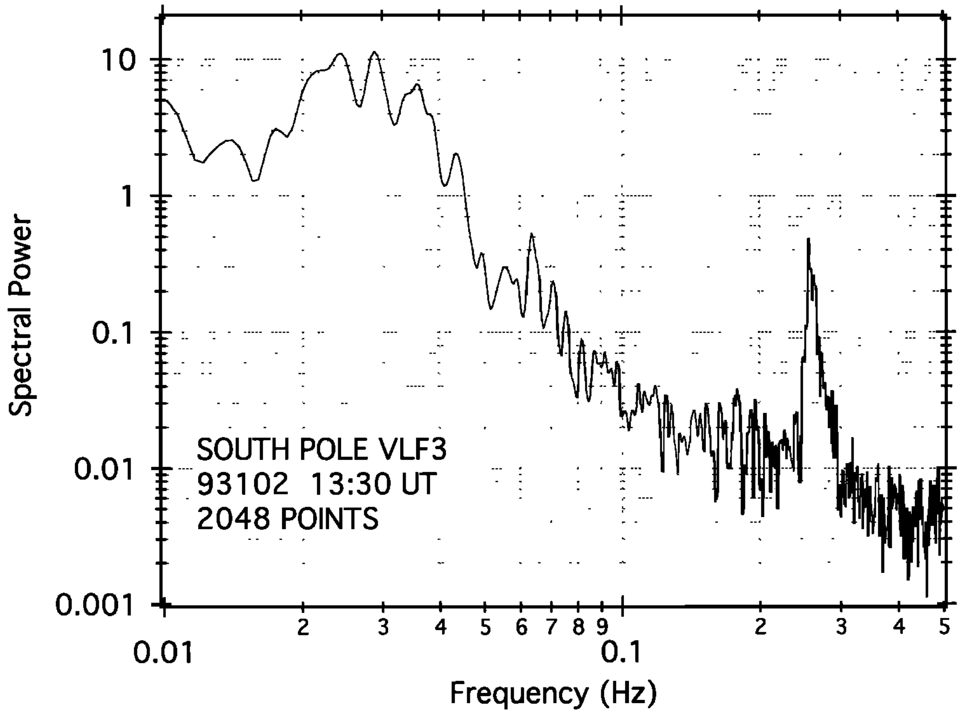

Figure 2. A line plot of the 0–500 mHz spectrum of a selected interval of the South Pole VLF3 data shown in Plate 1, for day 102 (April 12) 1993. A 2048-point sample and 5-point smoothing were used. The spectrum represents the time interval 1330:00–1404:07 UT. The logarithmic y axis in spectral power has an arbitrary origin.

ure 2 represents the structure of the spectrum in the SP 3.0-kHz channel, averaged over 34 min (1330–1404 UT), and clearly shows the two modulation bands centered at about 30 and 250 mHz, respectively. Plate 2 is another example, on May 21, 1995, in which the two bands were observed over many hours, in this case ~0900–2000 UT; Figure 3 contains plots for this day representing line spectra at three different times during the interval of falling QP (type II) and PE frequencies (see discussion below). At other times, either QPs or PEs may occur alone, although, as we describe later, QPs seem always to be accompanied either by Pc3/Pc4 pulsations (type I) or by PEs (type II), or by both.

The QP modulation bandwidth can vary considerably from event to event (see Figures 4a and 4b) but it tends to be larger for type I than type II QPs, as implied by *Sazhin and Hayakawa* [1994]. This is seen for example on May 21, 1995 (the peaks at 20 mHz in Figure 3c and 80 mHz in Figure 3a, respectively). In the plot the frequency scale is logarithmic so bandwidths at different frequencies are comparable if normalized to the centre frequency, i.e., are defined as $1/Q \equiv \Delta f/f_0$.

When the second harmonic of the PE frequency falls within the analysis band of 0–500 mHz (i.e., the fundamental frequency is less than 250 mHz), a second harmonic component is often observed (e.g., Figure 4c), because of the normally nonsinusoidal character of the amplitude envelope. Several instances are seen in Plate 2, e.g., around 2000 UT in the 3-kHz channel. On the rare occasions when the PE modulation frequency drops below (500/3) mHz, the third harmonic can also be observed. An example is seen in the 2.0-kHz channel at HB on June 29, 1993, at 1115 UT (Figure 4d), which shows peaks at about 160, 320, and 480 mHz. Interestingly, the QP modulation rarely exhibits any harmonics; when they do occur, they are weak and the waveform tends to have triangular maxima and rounded minima.

4.2. Frequency Variations

Modulation frequencies are sometimes observed to drift slowly on a timescale of hours. The drift is invariably in the downward direction, as also found by *Yamagishi et al.* [1984]. These events appear to be a distinct class which are not correlated with magnetic pulsations, i.e., they are always type II. When both QPs of this type and PEs are present, they both drift downward together. Such events are usually seen in the morning. Although it is not particularly obvious in the examples selected here, we have found from an examination of the full data set that this class of events predominates at HB compared to the higher-latitude stations. We infer that the source of the modulation is on relatively low L shells. This is consistent with a study by *Ho* [1973] of QPs observed at Eights station, Antarctica, in which both QPs and whistlers which they interacted were inferred to propagate within the outer plasmasphere, on L shells in the range 3.5–4.5.

Plate 2 and Figure 3 display an interesting example in which both types of QP are present on the same day. From about 0830 to 1130 UT we note a type II QP and a PE (with second harmonic) both with falling frequency, as well as a weaker but gradually intensifying type I QP with fairly constant modulation frequency of about 20 mHz, the same as that of the Pc3 which is most clearly seen at P3. At about 1215 UT, both the QPs and the PE suddenly weaken, coincident with a weakening of the Pc magnetic pulsation as seen at P2. The type II QP is more intense at HB than SP, implying a lower L shell than the type I for which the reverse is the case. One remarkable feature of the type II QP and the PE is that they seem to fall with the same rate of change of frequency. The frequency band occupied by the type II QP decreases from 70 to 90 mHz at 0930–1004 UT (Figure 3a) to 55–75 mHz at 1000–1034 UT (Figure 3b). This represents a rate of change of frequency of −0.5 mHz/min. The PE changes from 240–290 mHz to 230–260 mHz over the same interval, i.e., changing at a very similar rate of about −0.7 mHz/min. The significance of this is not clear. As far as one can tell from the 0–500 mHz spectra, the second harmonic, as expected, varies in frequency twice as rapidly. The magnetic pulsation (Figures 3d–3f) continues fairly steady at ~20 mHz, though with considerable variability from station to station and interval to interval.

On rare occasions type I events rise and fall in modulation frequency (two events out of the 131 listed in Tables 2 and 3), but in all instances we have observed, the QP frequency tracks with the Pc3 frequency and the magnitude of the IMF.

4.3. QP Occurrence Statistics and Correlation With Pc3 Pulsations

Both QPs and PEs are relatively common. During the first 152 days of 1993, for example, QPs were observed at HB on 38% of days. A more detailed study of QP occurrence at South Pole and P2 in 1993 and P3 in 1995 showed that in 667 station-days examined, there were 335 QP events. Our occurrence rates are rather high compared with those reported in previous studies, for example, by *Ho* [1973], who found only 46 QPs in a year of 1964–1965 (solar minimum) Eights data. The difference may be partly explained by the different identification techniques; Ho used narrowband filtered data whereas our filters are quite broad. *Sato et al.* [1974] quote the somewhat larger figure of 80 hourly occurrences rates at local noon for a year of 1970–1971 (solar maximum) Syowa data. This may point to a solar cycle dependence, although the figure is not directly comparable with Ho's event counts, since short events occurring away from noon are not included. Our larger occurrence rates, measured at an intermediate phase of the solar cycle, probably arise because our spectrogram display technique is very sensitive to any periodicities

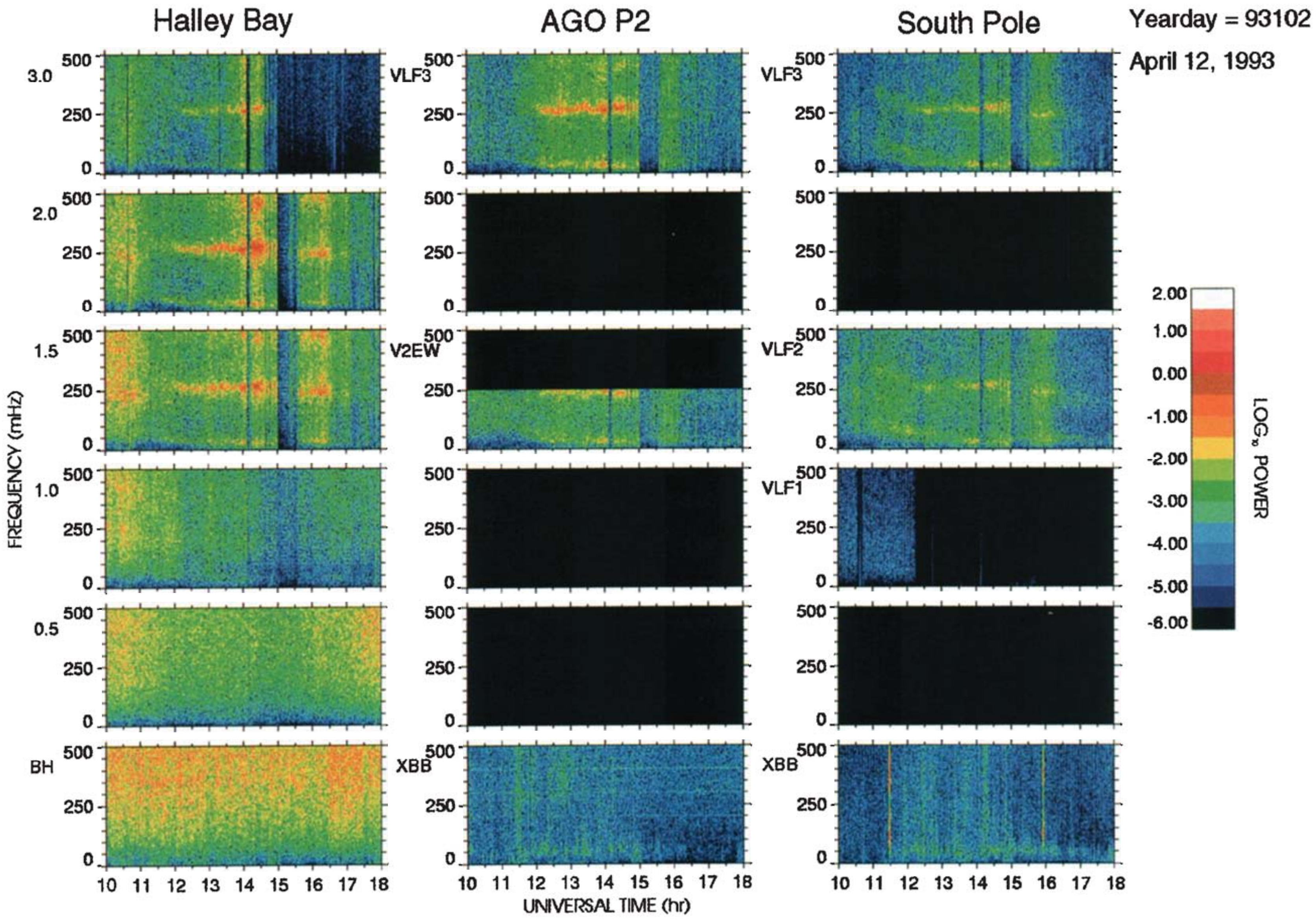

Plate 1. Composite stacked spectrogram plot for 1000–1800 UT, day 102 (April 12) 1993. Each column of plots shows data from one of the three stations HB, P2, SP from left to right. The lowest panel in each column shows a 0–500 mHz spectrogram of one component of the magnetic field (X_{BB} at SP and P2 and B_{H} at HB). The other panels show 0–500 mHz spectrograms of the amplitude measured in each of a number of ELF-VLF frequency bands, increasing in frequency upward. Corresponding bands are in line horizontally. The color scale represents spectral power (in relative units).

in the data, and responds well even to very weak events, provided that they are well-modulated.

The presence or absence of accompanying PE or Pc3–Pc4 activity is shown in Tables 2–4. A very high proportion (83% overall) of QPs were accompanied by PEs. This, together with the remarkable fact that all type II QPs were accompanied by PEs, suggests the possibility that the latter may be involved in the generation of type IIs; we will discuss this hypothesis later.

There are occasions when there is a very high correlation between the geomagnetic pulsations and the QP emissions observed at a particular location, as has been found in much previous work (type I QPs). *Engebretson et al.* [1990, 1991] showed examples of magnetic and QP events with spectral peaks both governed by the magnitude of the IMF. *Morrison et al.* [1994] confirmed those correlations and went on to examine correlations in the time series data, finding that there was usually no one-to-one correlation between the waveforms of the QPs and Pc3s. Figures 4a and 4b show the spectral correlation clearly. Other events are not correlated at all (type II), e.g., at SP and P2 on 12 April before 1200 UT (Plate 1). Sometimes the situation is more complex, with some degree of anticorrelation occurring.

QP events are known to be essentially a dayside phenomenon [*Ho,* 1973; *Sato et al.,* 1974; *Kimura,* 1974; *Morrison et al.* 1994] and can last for many hours at the same local time being observed by ground stations widely spaced in longitude as each rotates into the region of activity [*Smith et al.* 1991]. Even at a single ground station, events can be observed for more than an hour [*Ho,* 1973; *Lanzerotti et al.* 1986]. PE events can also be sustained for hours, though at other times they last only for tens of minutes; unlike QPs, they can be observed at Halley at any local time.

4.4. Dropouts

At times the entire VLF/ELF signal across a very wide band of carrier frequency, including any PE or QP emissions, will drop to noise level in a time of order 1 min, remain there for some minutes, and then usually but not always recover to previous levels with a similar time constant. Examples can be seen at about 1400 UT and 1500 UT on April 12 (Plate 1). The effect is spatially widespread, being observed simultaneously at all stations. These dropouts do not generally have any corresponding signature in the magnetic pulsations. This dramatic and puzzling phenomenon has been recognized for many years (D. L. Carpenter, private communication, 1984) but is as yet unexplained, though it may be a consequence of "holes" in the trapped resonant particle fluxes [*Smith,* 1995]. Alternatively, it could be related to the cutoffs in ducted whistler propagation by horizontal ionospheric density gradients reported by *Clilverd et al.* [1992]. Another possible mechanism is the effect of pressure pulses in the solar wind compressing the dayside magnetosphere and quenching the emission

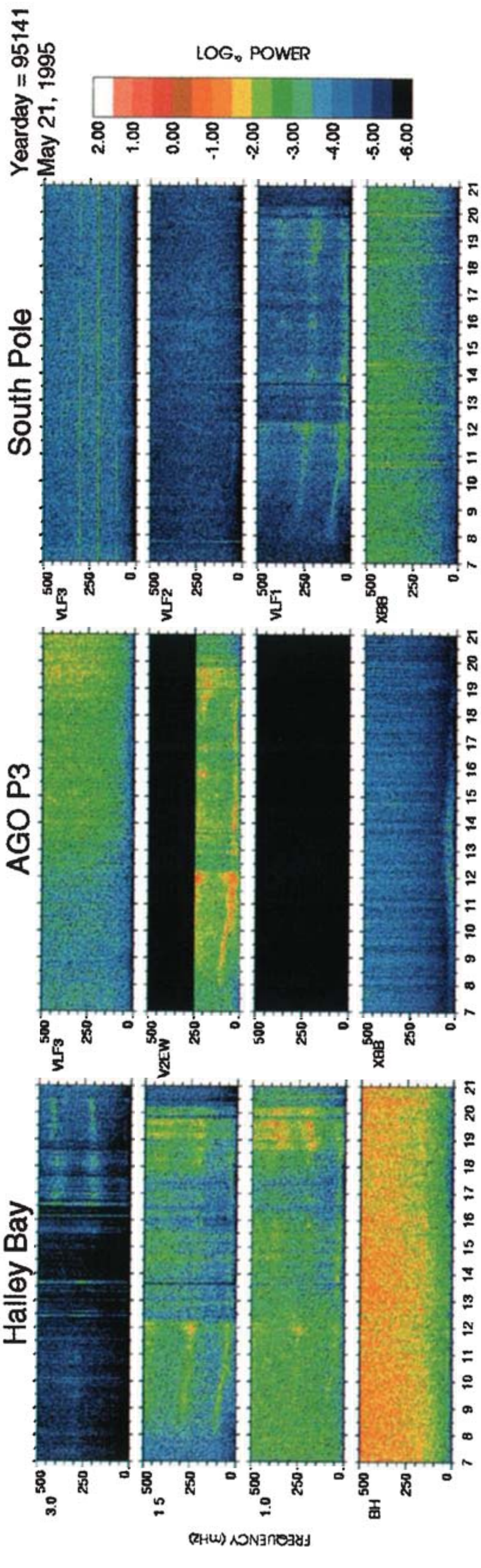

Plate 2. Similar to Plate 1 but for 0700–2100 UT, day 141 (May 21) 1995.

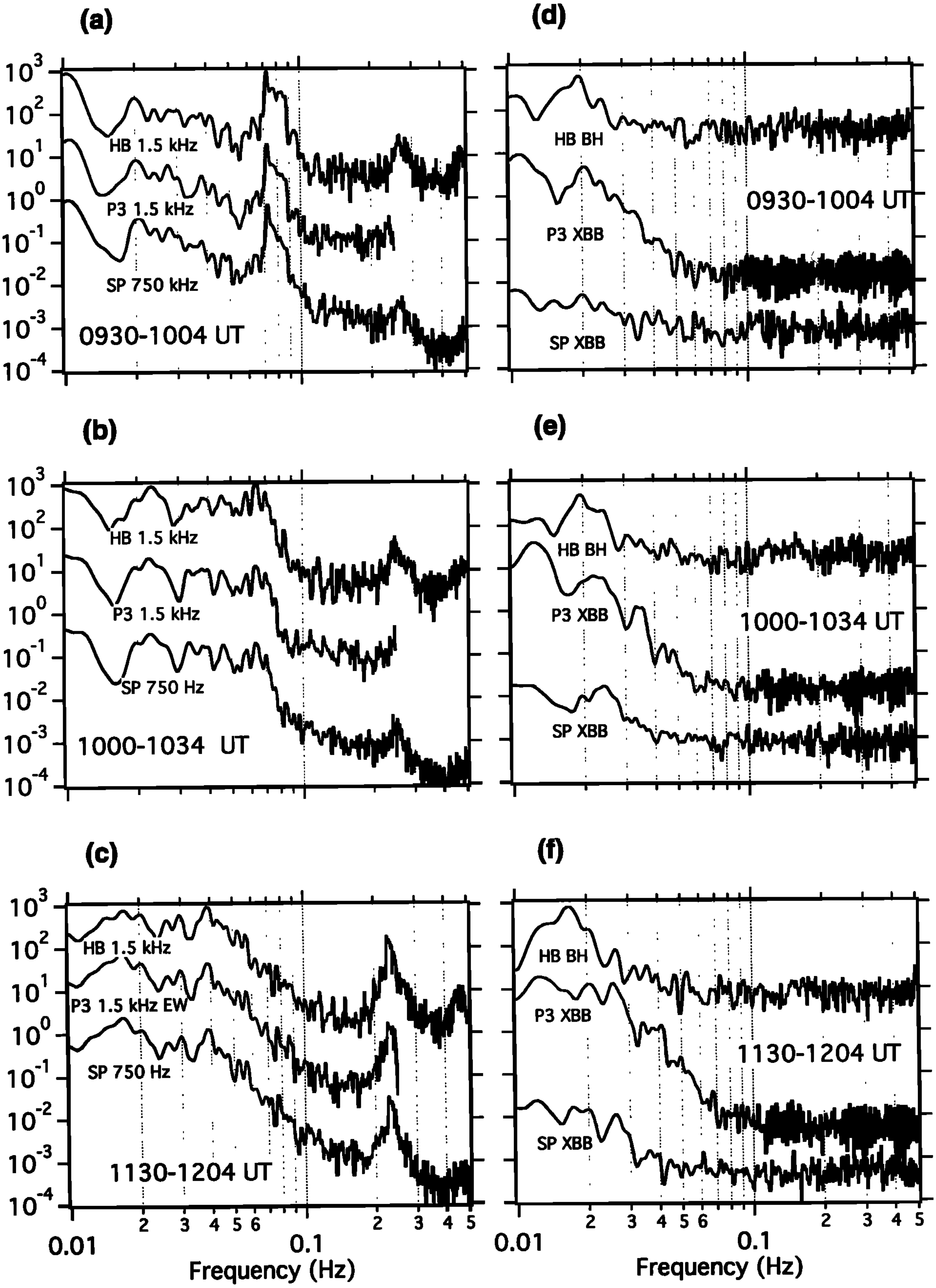

Figure 3. (a) Line spectra plot, similar to Figure 2, for 0930–1004 UT, day 141 (21 May) 1995, for the HB and P3 1.5-kHz channels and the SP 750-Hz channel. (b)–(c) As Figure 3a but for later times, 1000–1034 UT and 1130–1204 UT, respectively. (d)–(f) Line spectra of the magnetometer data, for the same intervals as Figures 3a–3c.

Table 2. QP Events Associated With Periodic Emissions (PEs) and Pc3–Pc4 Activity Observed at South Pole During the Whole of 1993 (365 Days)

	With PE	Without PE	Total
With Pc3/4 (type I)	85 (44%)	33 (17%)	118 (62%)
Without Pc3/4 (type II)	74 (39%)	0 (0%)	74 (39%)
Total	159 (83%)	33 (17%)	192 (100%)

Table 3. QP Events Associated With Periodic Emissions (PEs) and Pc3–Pc4 Activity Observed at P2 for 151 Days, January 1 to May 31, 1993

	With PE	Without PE	Total
With Pc3/4 (type I)	46 (57%)	16 (20%)	62 (77%)
Without Pc3/4 (type II)	19 (23%)	0 (0%)	19 (23%)
Total	65 (80%)	16 (20%)	81 (100%)

generation; a preliminary examination of a small set of IMP 8 and Wind data did not show a clear correlation of such pulses with observed dropouts, though this remains the subject of further investigation.

5. Discussion

QP VLF emissions are basically a predominantly dayside phenomenon, in spite of the few events which are observed predawn and postdusk. Events which are closely correlated with coincident geomagnetic pulsations (type I) are likely to be caused by quasiperiodic fluctuations in the resonant conditions at the VLF/ELF wave generation region, governed by the magnetic field oscillations [*Kimura,* 1974]. Compressional waves, probably caused by the effect of upstream waves, propagate inward from the magnetopause and appear to drive both QP modulation of VLF/ELF whistler mode waves, and field line resonances [*Morrison,* 1990; *Engebretson,* 1990, 1991]. The fact that harmonics of the QP modulation band are rarely seen lends support to the view that a linear resonance effect is responsible. Since type I QPs are often seen simultaneously at both HB and SP (see, e.g., Plate 1), the generation region is probably between the two, i.e., is located at quite a high L value though still on closed field lines, probably just inside the cusp, as suggested by *Lanzerotti et al.* [1986]. The source region may be either near the equatorial plane or at high-latitude [*Morrison et al.* 1994; *Alford et al.* 1996].

The larger modulation bandwidth for type I compared with type II QPs is expected according to our interpretation of the data. The former is presumably determined by the upstream wave source of Pc3 pulsations which is band-limited but not "narrow" with the center frequency determined by the magnitude of B (IMF); $\Delta f/f_0$ is typically 0.5–1 . We would expect the proposed type II QP source (see below) to be intrinsically more narrowband, as it is determined by ULF field line resonance conditions.

The fact that type II QPs and PEs always occur together and drift in frequency together (though the frequencies and drift rates are not harmonically related) suggests that they may be linked. *Ho* [1973] reported several examples of events in which whistlers appeared to interact with QP emissions seen at Eights station (located at a similar latitude to Halley), usually disrupting a QP pattern though occasionally initiating one. In our much larger data base of events than Ho's 19 events we have not noticed a strong interaction with whistlers, though this requires further investigation and quantification; however, echoing whistlers are closely related to periodic emissions, and thus our results and Ho's are probably connected. One probable link between type II QPs and PEs is electron precipitation into the lower ionosphere, as suggested by *Sato and Matsudo* [1986]. It is known that echoing whistler emissions, which are being strongly nonlinearly amplified in a narrow frequency range in a spatially confined field-aligned duct,

Table 4. QP Events Associated With Periodic Emissions (PEs) and Pc3–Pc4 Activity Observed at P3 for 161 days, January 26 to July 5, 1995

	With PE	Without PE	Total
With Pc3/4 (type I)	38 (61%)	7 (11%)	45 (72%)
Without Pc3/4 (type II)	17 (27%)	0 (0%)	17 (27%)
Total	55 (89%)	7 (11%)	62 (100%)

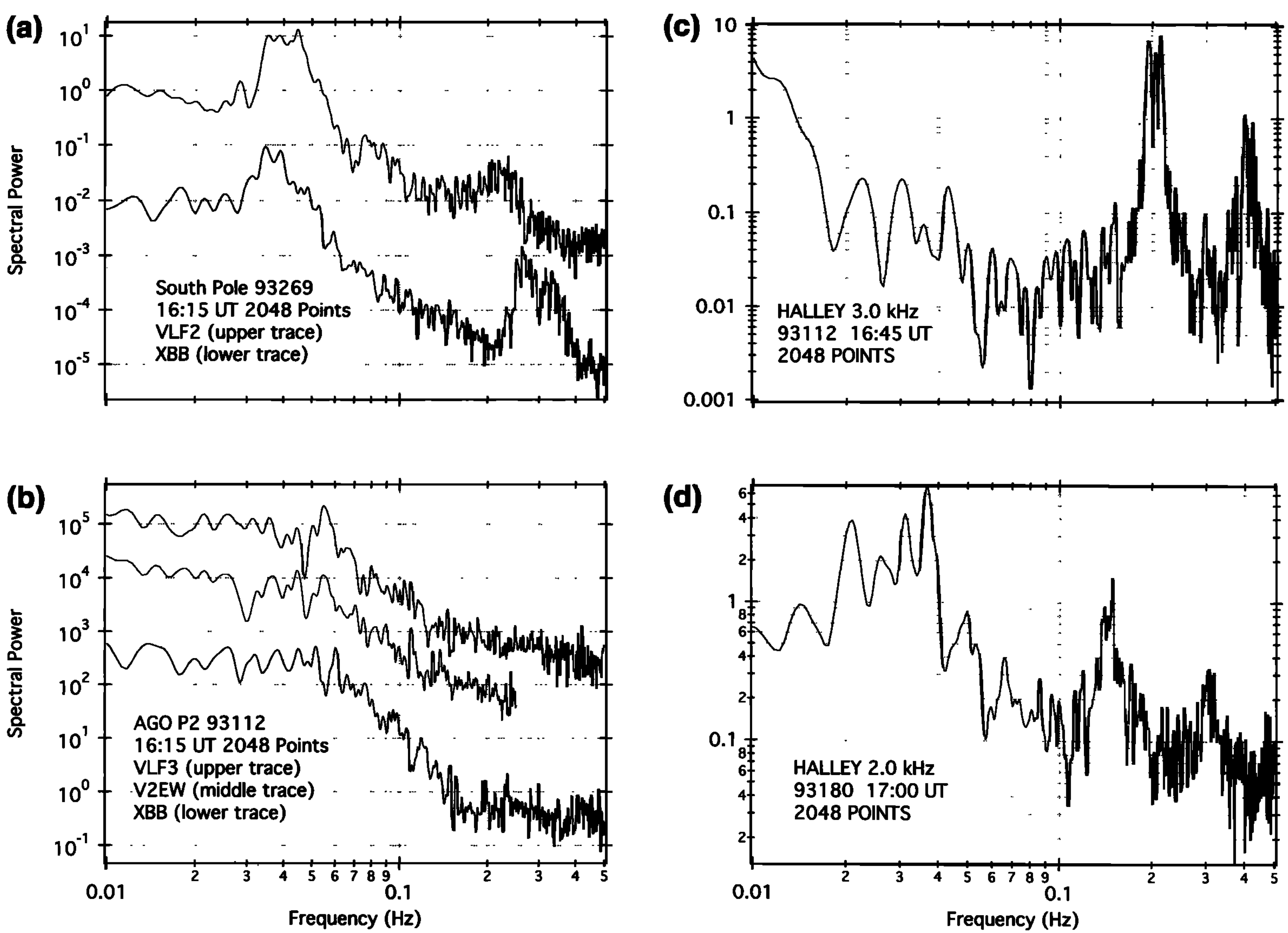

Figure 4. Plots of 0–500 mHz spectra in the same format as Figure 2. (a) SP, channels X_{BB} and VLF2, for 1615:00–1649:07 UT, day 269 (September 26) 1993. For clarity, the traces have been offset vertically. VLF2 shows a quite narrow QP type 1 bandwidth, of around 10 mHz at ~40 mHz. The spectrum of the Pc is similar. (b) P2, channels X_{BB}, VLF2EW and VLF3, for 1615:00–1649:07 UT, day 112 (April 22) 1993. Here we see an example of a much broader band QP event, with a plateau extending up to about 150 mHz; again, this is reflected in the bandwidth of the coincident geomagnetic pulsations. (c) HB, 3.0-kHz channel, for 1645:00–1719:07 UT, day 112 (April 22) 1993. First and second harmonic peaks are seen, centered at 200 and 400 mHz. (d) HB, 3.0-kHz channel, for 1700:00–1734:07 UT, day 180 (June 29) 1993.

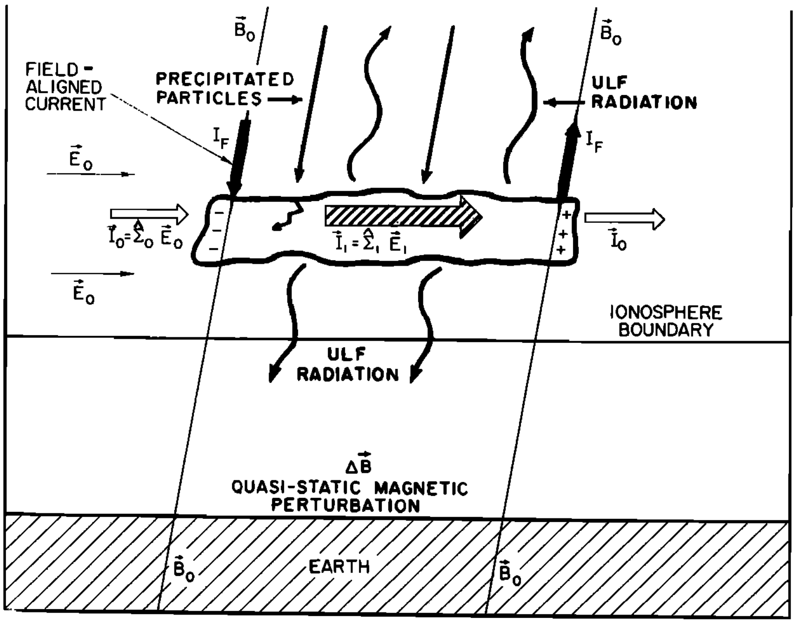

Figure 5. Possible mechanism for generation of ULF waves through precipitation by VLF periodic emissions [from *Bell,* 1976]. A region of enhanced ionospheric current flow, I_i, due to enhanced conductivity Σ_i produced by particle precipitation with horizontal scale size of order 100 km, drives field-aligned currents I_F and ULF waves.

scatter electrons into the loss cone [*Dingle and Carpenter,* 1981]. These electrons then precipitate causing density and conductivity enhancements at D region and lower E region altitudes [*Clark and Smith,* 1990]. This process could drive field-aligned currents which generate Alfvén waves that set up a field line resonance on the flux tube of the whistler duct [*Bell,* 1976]. The oscillating magnetic field in the whistler source region would modulate the overall amplitude envelope of the VLF emissions, by modulating the electron cyclotron resonance conditions, in the same way as for type I QPs. However, the magnetic ground signature would be small because the ionospheric currents would be largely field-aligned, and the cross-field currents would be highly localized within the narrow footprint of the magnetospheric duct, as shown in Figure 5. This process would tend to be more efficient at lower latitudes where the field lines are shorter, and would imply that type II QPs tend to occur at generally lower latitude compared with type I. There is some evidence that this may be the case (section 4.2). Successive whistler mode echo trains are not generally phase coherent, so the above mechanism would be consistent with the lower-frequency modulations being only quasiperiodic. An alternative possibility that the pulsations may actually be tied to the whistler ducts themselves in some way not yet understood, as suggested recently by *Verö et al.* [1997] based on magnetic and whistler observations at $L \simeq 2$.

The downward frequency drifting which is sometimes observed, especially in the morning, may be a result of density changes on the magnetospheric propagation path. As the observing station rotates eastward past dawn, solar photoionized plasma will diffuse up the magnetic flux tubes and increase the plasma density at high altitude. The increased density will increase both the field line resonance period $2\int v_A^{-1} ds$ (reduced Alfvén velocity v_A) and the whistler echo period $2\int v_g^{-1} ds$ (reduced whistler mode group velocity v_g) [*Yamagishi et al.,* 1984]. Both v_A^{-1} and v_g^{-1} are proportional to the square root of the plasma density, so provided the density distribution along the flux tube is constant, the frequency drift from this effect should be proportional to frequency rather than independent of it as observed. This will not necessarily be the case for a nonequilibrium situation, in which the density distribution along the field line changes as the flux tube fills, because v_A and v_g depend in different ways upon the magnetic field and thus upon s the integration variable in the field line integrals quoted above. An alternative explanation is that the whistler duct supporting the propagation of whistler mode waves to the ground could be convecting outward, as would be expected on the dayside of the magnetosphere. This would have the effect of increasing the length of the flux tube and thus both the period of the field line resonance on that tube and the whistler mode echo time.

6. Summary and Conclusions

We have examined the available ELF/VLF and magnetic data from two manned and two unmanned Antarctic observatories (Halley, South Pole, and AGOs P2 and P3) for two year-long intervals (1993 and 1995). We have used a technique in which Fourier transformed time series of VLF wave amplitude and magnetic field data are displayed as color spectrograms. This is an effective tool for identifying and studying periodic and quasiperiodic ELF/VLF emissions and associated geomagnetic pulsations.

Many previously reported properties of such events have been confirmed. Periodicities in the ELF/VLF data are usually seen in two bands: 10–100 mHz (quasiperiodic) and 200–300 mHz (periodic). QPs occur mainly on the dayside and may be classified into two types (conventionally known as type I or type II depending upon whether or not they are accompanied by Pc3–Pc4 pulsations of similar period). Our data are consistent with the model that QPs are caused by field line resonances modulating the whistler mode wave growth rates in the high-altitude VLF/ELF source region and that PEs are the result of whistler mode echoing, mainly in the outer plasmasphere. The modulation frequencies of PEs and type II QPs often drift downward together on the timescale of hours, usually in the postdawn sector. This suggests that the two phenomena are colocated (see below), the drift being possibly a result of magnetospheric plasma density increases with local time or alternatively outward convection.

We have observed higher occurrence rates of QPs compared with previous studies, which may be because our data processing algorithm and display technique is particularly suited to extracting weak periodicities in the 0–500 mHz range.

Every one of the 345 QP events which we observed, was found to be accompanied either by Pc3–Pc4 pulsations of similar period (type I) or by PEs (or both). This suggests a close link between whistler propagation on relatively low L shells (typically within the plasmasphere) and type II QPs, as suggested in earlier work by *Ho* [1973]. We propose that type II QPs could be driven by PEs through the field-aligned currents produced by whistler wave induced electron precipitation. Our type I events without PEs are consistent with the model of such events being driven by upstream waves which cause compressional fast mode waves to propagate inward from the magnetopause; they probably occur on closed field lines near the magnetopause. For those events which occur with both magnetic pulsations and PEs, we may surmise that they are classic type I and that the PEs occur fortuitously and are not connected. Alternatively, there is the intriguing possibility that the pulsations may actually be linked to the whistler ducts in some way not yet understood.

Dramatic signal dropouts and recoveries, on a timescale of minutes, are unexplained; a speculation is that they may be related to holes in the resonant particle flux.

The results presented here raise many questions about the nature of QPs and their relationship to PEs and geomagnetic pulsations. The expanding network of automatic geophysical observatories in Antarctica, together with developments of the data processing techniques described here (to include for example cross-spectra between spaced observatories) should enable these questions to be addressed in future studies.

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