Latitudinal and seasonal variations of quasiperiodic and periodic VLF emissions in the outer magnetosphere

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[1] We have analyzed ELF-VLF receiver and search coil magnetometer data from five Antarctic stations from 1998 and 1999 to study quasiperiodic emissions (QPs) and periodic emissions (PEs), which occur as ULF-range modulations of ELF-VLF signals between 0.5 kHz and ~4 kHz. QPs are modulated at frequencies of ~20–50 mHz, and PEs are modulated at frequencies of ~200–500 mHz. The stations used covered a range of magnetic latitudes from −62° (Halley) to −74° (South Pole Station); three automated geophysical observatories (AGOs) were located at intermediate latitudes. Consistent with earlier studies, most QPs were observed with magnetic pulsations of identical period in the Pc3 range (type I QPs). Of those QPs not observed with simultaneous magnetic pulsations (type II QPs), nearly all were accompanied by PEs. Type I QPs, PEs, and events during which both appeared together (QPPEs) were found to have different latitudinal, seasonal, and diurnal occurrence patterns: QPs of both types were more likely to occur between −65° and −70° magnetic latitude, while PEs occurred more often around −60° magnetic latitude. QPs were more common during the months of October though March, while PEs were more common during the months of May through September. QPs, whether with or without simultaneous PEs or magnetic pulsations, were predominantly a dayside phenomenon, with a broad maximum near local noon. The occurrence of QPs unaccompanied by PEs was restricted to the dayside, however, while a small number of QPPEs appeared even during nighttime hours. PEs, on the other hand, could be seen at all local times, but with latitudinally dependent diurnal patterns. Most higher-latitude QPs were type I events (observed with magnetic pulsations), while type II QP events (without simultaneous magnetic pulsations) occurred relatively more often at lower latitudes. A case study from 1 August 1999 using wideband data from South Pole and Halley provides evidence of a transition from echoing whistler activity to PE activity and then to QP activity and suggests a causal relationship. *INDEX TERMS:* 2772 Magnetospheric Physics: Plasma waves and instabilities; 2752 Magnetospheric Physics: MHD waves and instabilities; 2483 Ionosphere: Wave/particle interactions; 7867 Space Plasma Physics: Wave/particle interactions; *KEYWORDS:* ULF pulsations, Pc3-4 pulsations, Pc3 pulsations, quasiperiodic emissions, periodic emissions, VLF waves

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1. Introduction

[2] Observations of naturally occurring electromagnetic emissions in the lower audio frequency range go back to the early decades of the twentieth century, when they were adventitiously detected by early radio receivers. Whistlers and other ELF and VLF signals propagating through Earth's magnetosphere are now the object of considerable study both intrinsically, and for their use as remote signals for diagnosis of ionospheric effects [*Helliwell*, 1965; *Park and Carpenter*, 1978]. Studies beginning in the 1950s at times focused on modulations of ELF and VLF signals in the 0.5 kHz–~4 kHz band at much longer periods, in the ULF range. Two major categories of such modulated emissions are now identified, known as quasiperiodic emissions (QPs) and periodic emissions (PEs), which typically occur with

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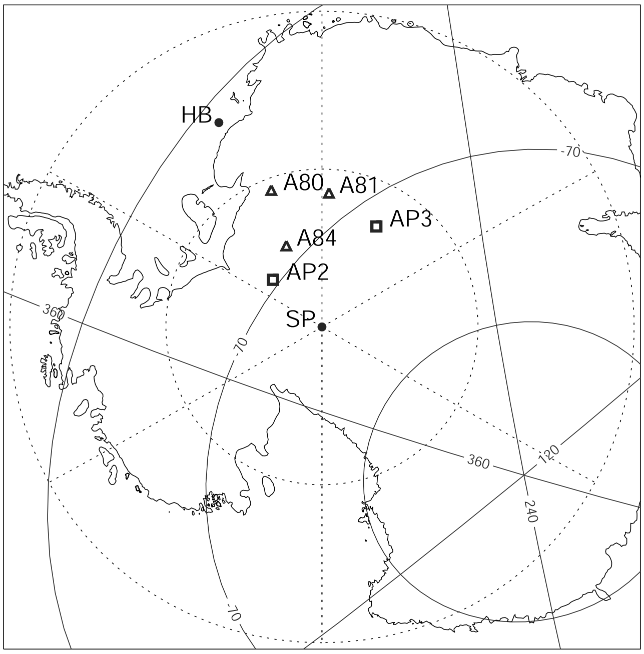

Figure 1. Map of Antarctica, showing the observatories from which data were used in this study: Halley (HB), BAS AGOs A80, A81, and A84, and South Pole (SP). Also shown for reference are the locations of U.S. AGOs P2 and P3, which were used in the *Smith et al.* [1998] study.

modulation frequencies of ~20–50 mHz and ~200–500 mHz, respectively. Both types of emission are now understood to be whistler mode waves of magnetospheric origin that have propagated through the ionosphere to the ground.

[3] The modulation period of PEs is usually a few seconds, similar to the two-hop travel time of echoing whistlers at the same frequency; they were therefore identified as bursts of whistler mode waves echoing along geomagnetically field-aligned ducts of enhanced plasma density between opposite hemispheres. The 10–40 second period of QPs, on the other hand, is the same as that of Pc3-4 magnetic pulsations. *Sato et al.* [1974] further classified QPs into two types. Type I QPs occurred in association with magnetic pulsations of similar period, while type II QPs were found to occur without magnetic pulsations.

[4] An early Antarctic study of QP events by *Ho* [1973] found that events observed at Eights, Antarctica (75°S, 77°W geographic, L = 3.9) tended to occur most often during the equinoxes, during late afternoon, and during quiet geomagnetic conditions. *Ho* [1973] noted that in nearly all cases, there was clear evidence of whistlers propagating along the same path, which in most cases was determined to lie between L ~ 3.5 and 4.5 and was within the plasmasphere.

[5] At higher latitudes, *Engebretson et al.* [1990, 1991] found numerous examples in data near local noon from South Pole Station, Antarctica of simultaneous Pc3-4 magnetic pulsations and QP emissions, at the same frequency. They also showed that these frequencies were proportional to the magnitude of the interplanetary magnetic field, and thus matched the values expected for an upstream wave source involving solar wind ions reflected from a quasi-parallel shock.

[6] Studies of QP events in Antarctica were continued by *Morrison et al.* [1994], who used ELF/VLF and magnetic field observations from South Pole Station (−74.2° MLAT), Siple Station (−60.8°), and Halley (−61.9°) to compare QP and Pc3 magnetic pulsations. They showed one example in which QP signals occurred in phase (to within the 1-s sampling rate) at each station, while the simultaneously observed Pc3 activity showed no coherence between stations. This was attributed to a single (or at least localized) magnetospheric source of the QP signals, as well as the larger fields of view of the ELF/VLF receivers compared with those of the pulsation magnetometers.

[7] More recently, *Smith et al.* [1998] used data from South Pole, Halley, and the P2 and P3 AGOs (Automated Geophysical Observatories), displayed in the form of differenced FFT spectrograms, to explore the relations between QP events and PE events. Among other findings, this study found a strong association between PE events and the simultaneous appearance of type II QPs.

[8] This paper follows up on the work of *Smith et al.* [1998] by incorporating a larger data set from a latitudinal array of Antarctic stations. Two yearlong multistation data sets, covering 1998 and 1999, were used to provide information on seasonal, diurnal, and latitudinal variations in occurrence of QP and PE emissions that occur with or without Pc3-4 magnetic pulsations. Because of the very similar results from both years, however, only the 1998 data will be presented in full. Both these statistical studies and a case study of one extended event observed at these stations provide further evidence of a strong link between PEs and type II QPs.

2. Data Set

[9] The data used in this study comes from five Antarctic stations: South Pole Station (SP), operated by the United States; Halley (HB), operated by the British Antarctic Survey (BAS); and three automated geophysical observatories (AGOs), A80, A81, and A84, also operated by BAS. We used data from VLF/ELF receivers at all stations and search coil magnetometers at A80, A81, A84 and SP. The locations of these stations are shown in Figure 1, and their magnetic latitudes and magnetic longitudes can be found in Table 1. A80, A84 and HB lie close to the same meridian, with A81 about 10° to the east and SP about 10° to the west. This figure also shows for comparison the locations of U.S. AGOs P2 and P3, which were used in the *Smith et al.* [1998] study.

[10] The instrumentation at South Pole Station is described by *Engebretson et al.* [1997]. Pc3 pulsations are

Table 1. Locations of the Antarctic Stations Used in This Study

Site	Geographic Lat	Geographic Long	Geomagnetic Lat	Geomagnetic Long	L Shell	MLT of Noon
Halley	75.6°S	26.3°W	61.9°S	28.3°E	4.5	1424
AGO A80	80.7°S	20.4°W	66.5°S	28.5°E	6.3	1448
AGO A81	81.5°S	3.0°E	68.9°S	35.8°E	7.7	1420
AGO A84	84.4°S	23.9°W	69.2°S	25.7°E	8.1	1505
South Pole	90°S	–	74.0°S	18.4°E	13.5	1530

Table 2. Event Categories Used in Statistical Studies of QP and PE Events

Type of Event	Classification of Event
QP Type I only (QP 1)	An event (with center frequency) between 0 and 100 mHz, without any PEs, but with Pc3 pulsations occurring sometime during it.
QP Type II only (QP 2)	An event between 0 and 100 mHz without any PEs or Pc3 pulsations during it.
PE Type I only (PE 1)	An event between 100 and 500 mHz without any QPs, but with Pc3 pulsations during it.
PE Type II only (PE 2)	An event between 100 and 500 mHz without any QPs or Pc3 pulsations during it.
QP and PE Type I (QPPE 1)	An event in which a QP and a PE are seen overlapping in time, and which also has a Pc3 pulsation during at least part of the QP.
QP and PE Type II (QPPE 2)	An event during which a QP and a PE are seen overlapping in time, but which has no Pc3 pulsation.

recorded by the University of New Hampshire-Augsburg College 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. The ELF/VLF data come from the Stanford University receiver, which provides 1-second samples in several bandpass channels [*Shafer et al.*, 1994]. Because QP events rarely if ever appear at frequencies above 3 kHz, we used the three lowest frequency channels, spanning 0.5–1.0 kHz; 1.0–2.0 kHz, 2.0–4.0 kHz, and with center frequencies 0.75, 1.5, and 3.0 kHz respectively. Wideband data (0–17 kHz) are also recorded at intervals; for this paper we use the broadband data in the form of 1-min-long 0–5 kHz spectrograms sampled every 15 minutes.

[11] The Halley VLF data are principally from the VELOX (VLF/ELF logger experiment) instrument [*Smith*, 1995] which has eight channels in the 0.3–10 kHz range, though here we are concerned only with three of the lower frequency channels which have center frequencies (and bandwidths) in kHz of 0.5 (0.5), 1.0 (1.0), and 2.0 (1.0). In this paper we use the VELOX amplitude data, which are sampled and stored once per second. Synoptic broadband VLF goniometer receiver data from 0 to 22 kHz were also recorded for 1 min at 15-min intervals [*Smith and Nunn*, 1998]; for this paper we again use 0–5 kHz spectrograms.

[12] The VELOX instrument at the BAS AGOs is similar to that at Halley, but until 1998 had a reduced number of channels [*Dudeney et al.*, 1997]. In this study we use channels with the same center frequencies and bandwidths as the Halley channels mentioned above. An Augsburg College-University of New Hampshire search coil magnetometer [*Arnoldy et al.*, 1998] is also included at each BAS AGO. These instruments measure the rate of change of the ambient geomagnetic field at a rate of 2 samples per second.

3. Statistical Study

3.1. Procedure

[13] From the magnetic field and ELF/VLF data sets described in the preceding section, we produced 0–24h 0–500 mHz differenced spectrograms for each station for every day during 1998 and 1999 when the data were available; these were then examined to identify QP and PE events. Technical details about the production of the spectrograms, and the appearance on them of the PE and QP events, were documented by *Smith et al.* [1998]. For 1998, South Pole was missing 11 days, A81 was missing 5 days, A80 was missing 67 days, and Halley was missing 8 days. For 1999, South Pole was missing 10 days, AGO A84 was missing 92 days, AGO A80 was missing 3 days and Halley was missing 21 days. We included an event if it displayed an ELF/VLF power enhancement of at least three shades above the surrounding background noise (an increase of 15 dB) for at least 30 minutes. [Sixteen color levels correspond to a factor 10^8 in power, i.e., 80 decibels, so one level = 5 dB.] In order to reject intensifications of broadband noise, we selected only those events with a bandwidth $\leq$100 mHz. Once QP and PE events were identified, we used the magnetometer data to categorize them as Type I or Type II. We further categorized each QP event according to whether or not it occurred simultaneously with a PE, in order to further investigate the correlation between QPs and PEs that was first seen in the *Smith et al.* [1998] study. The event classification scheme is given in Table 2. In this table and in the following sections, Arabic numerals 1 and 2 are used in these six categories to distinguish them from the QP 1 and QP II categories used above, which were defined without regard to the simultaneous occurrence of PEs. As noted in Table 2, the frequency boundary between QP and PE events was 100 mHz. In practice, however, few events occurred between 50 and 200 mHz. If an event was found to begin in this region, we looked to see whether it was rising toward a PE or descending to a QP, and thus classified it as a PE or QP respectively.

[14] The immediate result of this survey of the data was a yearly list of events of each type at each station, with starting and ending dates and times. Individual events often fell into the same category at each station, but in many cases individual events were observed at only a subset of the stations, and in 5–10% of the cases identifications based on ELF-VLF data from individual stations led to differing categories for what appeared to be the same event. Also, because no search coil magnetometer data were available at Halley, for this station we relied on magnetic field data from the nearest AGO, A80.

[15] These observational complexities led us to also construct a combined "all-station" categorization of each event. Each event would be characterized according to whether QPs, PEs, and/or magnetic pulsations appeared simultaneously at even a non-overlapping subset of the stations. For example, an event categorized as a QP 2 at one station and as a PE 2 at another, if observed simultaneously, would be designated overall as a QPPE 2 event. In most cases for which this complication arose, QP or PE signatures appeared at all stations, but at some stations were too weak to meet the selection criteria described above. In particular, some events designated as QP 2 at individual stations, especially at higher latitudes, were designated QPPE 2 in the all-station list.

[16] Table 3 shows the total number of occurrences in any 2-hour interval for the four categories of QP emissions (QP 1, QP 2, QPPE 1, and QPPE 2) for 1998, totaled for

Table 3. Total Number of Occurrences in Any 2-Hour Interval for the Four Categories of QP Emissions During 1998 at Halley, AGO A80, AGO A81, and South Pole Station[a]

Station	Days	With PE	Without PE	Total
SP	354			
With Pc3-4 (type I)		57 (43%)	62 (47%)	119 (90%)
Without Pc3-4 (type II)		8 (6%)	5 (4%)	13 (10%)
Total		65 (49%)	67 (51%)	132 (100%)
A81	360			
With Pc3-4 (type I)		58 (26%)	130 (58%)	188 (84%)
Without Pc3-4 (type II)		28 (12%)	9 (4%)	37 (16%)
Total		86 (38%)	139 (62%)	225 (100%)
A80	298[b]			
With Pc3-4 (type I)		96 (32%)	145 (49%)	241 (81%)
Without Pc3-4 (type II)		46 (16%)	9 (3%)	55 (19%)
Total		142 (48%)	154 (52%)	296 (100%)
HB	357			
With Pc3-4 (type I)		42 (26%)	87 (54%)	129 (80%)
Without Pc3-4 (type II)		28 (17%)	5 (3%)	33 (20%)
Total		70 (43%)	92 (57%)	162 (100%)

[a]The four categories of QP emissions are QP 1, QP 2, QPPE 1, and QPPE 2.
[b]No data were available for October or November at A80.

each station, in order to compare with the tables of *Smith et al.* [1998] for data from 1993.

[17] A comparison of Table 3 with the results shown in Tables 2–4 of *Smith et al.* [1998] reveals that for both data sets type I QP events greatly outnumber type II QP events. The ratio of QPPE 1 and QPPE 2 events was also quite similar (near 2:1) at all auroral zone stations (AGOs P2 and P3 in 1993, and AGOs A80 and A81 in 1998) in both years and at Halley in 1998, but differed greatly at South Pole (~1:1 in 1993 and ~7:1 in 1998). However, the data sets showed significant disagreement in the relative occurrence of PEs with QPs. During 1993 over 80% of all QP events occurred simultaneously with a PE at each observing station, but in 1998 less than half did so. Similarly, in 1993 the dominant category at all stations was QPPE 1, with QPPE 2 the second most common; in 1998 the dominant category at all stations was QP 1, with QPPE 1 the second most common.

[18] We believe the much greater number of occurrences without PE activity recorded in the 1998 data set reflects the more restrictive bandwidth, duration, and signal/noise criteria used in the current study; the appearance of relatively weak PEs in our differenced spectrograms is often more diffuse than QPs. This difference in criteria may be one cause of the difference in QP 2 occurrences as well: *Smith et al.* [1998] identified no QP 2 events, whereas in our study a small number (3–4%) of them were identified at each station.

[19] It is also notable that no events in the PE 1 category (periodic emissions simultaneous with Pc3-4 magnetic pulsations but without QPs) were observed during the entire year at any station. The *Smith et al.* [1998] study did not check for the presence or absence of magnetic pulsations at the same time as PE events; as far as we know, this is the first study to note the absence of such events.

3.2. Seasonal and Latitudinal Variations

[20] Studies over a decade ago by *Sato et al.* [1990, 1991] provided data on seasonal and long-term variations of daytime ELF/VLF emissions at two nearly conjugate auroral zone stations: Syowa in Antarctica and Husafell in Iceland. Using one year's intensity records in three frequency bands (750 Hz, 2 kHz, and 4 kHz), they found a maximum in emission occurrence at 750 Hz during local summer in both hemispheres. Data at 2 kHz revealed a summer maximum at Syowa, but no clear seasonal dependence at Husafell. Although these studies did not attempt to discriminate between the various types of ELF/VLF emissions, and in particular did not consider QP or PE events separately, it is notable that they interpreted the differing seasonal variations at Syowa and Husafell as due in part to propagation effects related to the presence of sunlight in the topside ionosphere.

[21] Although the data presented in this paper come from only one hemisphere, it provides information over a range of latitudes, as well as for each of the modulated emission types listed above. Figure 2 shows the seasonal occurrence patterns of each category of QP and PE events during 1998 at each individual station (upper four panels) and at all stations combined (the "all-station" categorization (bottom panel)). The panels are placed in order of decreasing magnetic latitude, from South Pole Station (SP) at near-cusp latitudes, through AGO A81 (or A84) and AGO A80 in the auroral zone, to Halley at subauroral latitudes.

[22] Figure 2 shows that the number of QP 1 occurrences maximizes in the auroral zone, and shows a slight decrease from the auroral zone toward both higher and lower latitudes, while the number of PEs increases monotonically toward lower latitudes. The presumed source of PEs near or inside the plasmapause is consistent with this distribution, while QP 1 events are thought to be formed outside of the plasmapause thus favoring the higher latitudes. The lower QP 1 occurrence at South Pole Station may reflect the fact that this station is sometimes within or poleward of the cusp region, where these events cannot reach. Comparisons with data from stations at intermediate latitudes will be needed to explore this possibility. The few QP 2 events and QPPEs of both types show no significant latitudinal trend.

[23] Figure 2 also shows that several categories of events exhibit a clear seasonal variation. QP 1 events dominate during the equinoxes and southern hemisphere's summer months (September through April) at most stations, while PE events tend to dominate during the southern hemisphere's winter months (May through September). The relatively few QP 2 and QPPE 2 events show little seasonal variation, while the QPPE 1 events show a modest increase during the southern hemisphere's summer, in a pattern that is suggestive of a convolution of the individual distributions of QP 1 and PE 2 occurrence. Very similar latitudinal and seasonal trends and overall occurrence rates were evident in the 1999 data, except that the relative occurrence of QPPEs of both types was somewhat reduced. Although this reduction might be attributed to a solar cycle variation, it could be an artifact of our analysis: different people analyzed the data from the two years.

[24] The all-station distributions in the bottom row of Figure 2 indicate that, although a large fraction of the events of each type appear at several stations, the relative occurrence rates differ considerably from station to station, so single-station studies would not reveal the overall pattern. In particular, at Halley many more PE events and fewer QP 1 and QPPE 1 events were observed than at stations in the

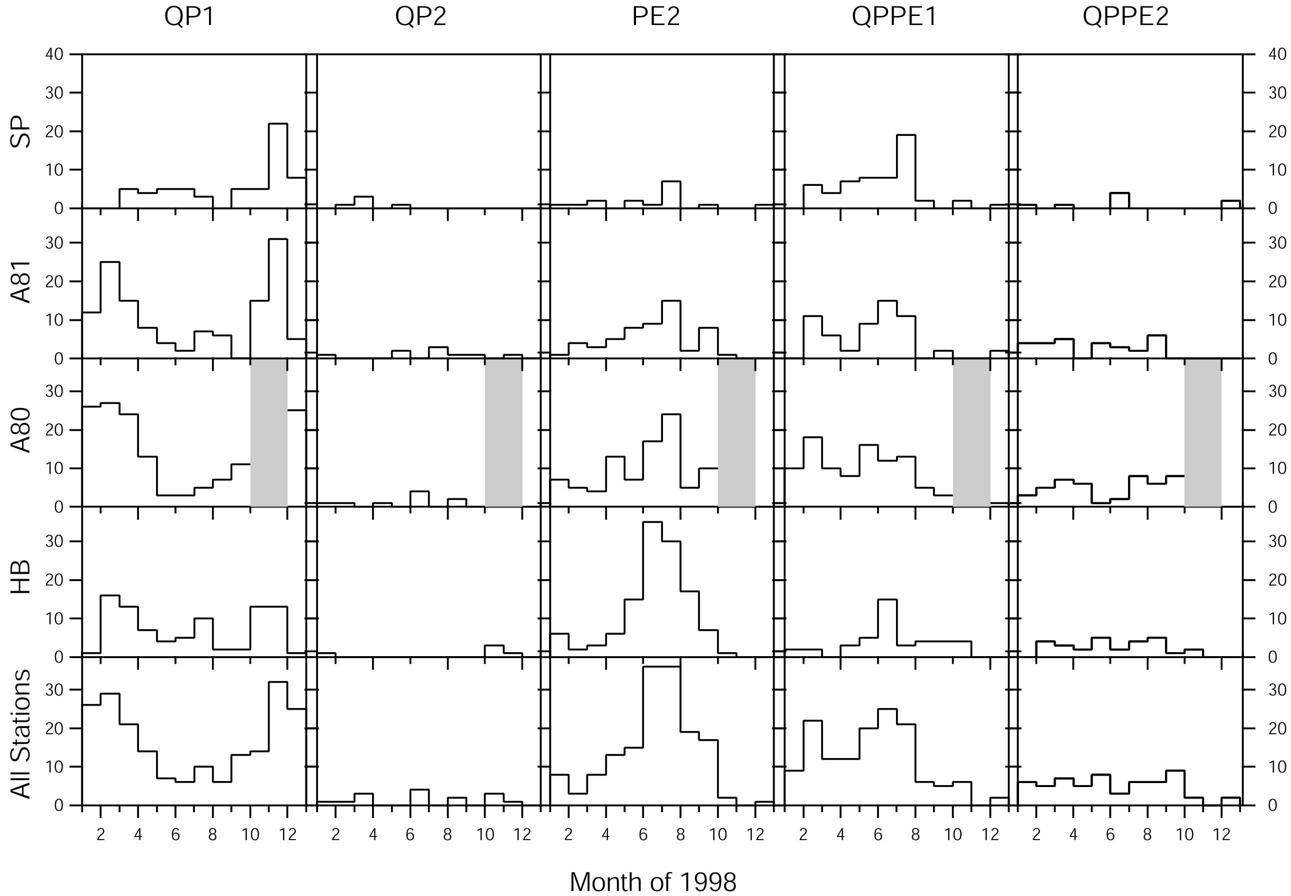

Figure 2. Monthly occurrence patterns of modulated ELF/VLF emissions in any 2-hour interval during 1998 in the QP 1, QP 2, PE 2, QPPE 1, and QPPE 2 categories are shown for each station (no PE 1 events were observed). The bottom panels show all "all-station" events, with all duplication among stations eliminated.

auroral zone, while conversely at South Pole many fewer PE events and fewer events overall were observed. We point out also that although the number of all-station QP 1 events is in all cases larger than or equal to the number at any individual station, for QP 2 events it is clear that in several months the all-station count is lower than the count at any individual station (for reasons discussed above). For most months the number of all-station PE 2, QPPE 1, and QPPE 2 events is larger than or equal to the number at any individual station, but there are exceptions for these categories too.

3.3. Diurnal Variations

[25] Figure 3 shows the distribution of "all-station" events observed during 1998, grouped into 2-hour bins in universal time. (Corresponding distributions of events observed during 1999 were similar.) Local magnetic noon at all stations is near 1500 UT.

[26] The distribution of QP 1 emissions shown in Figure 3a is restricted almost exclusively to daytime hours, with a broad distribution peaking near or shortly before local noon. A factor of 2–3 more events were observed during summer months at the auroral zone stations, but the latitudinal distribution was roughly the same at all stations during local winter. We believe, as did *Morrison et al.* [1994], that this diurnal pattern reflects the upstream wave source of the Pc3 pulsations that are associated with these QP events, while the seasonal variation in latitude may reflect differences in propagation characteristics: although fewer events occurred during winter, they were usually observed at all four stations. *Engebretson et al.* [2000] also noted, in a comparison between Pc3-4 observations at South Pole and Sondrestrom (both cusp-latitude stations) that pulsation power was greater at South Pole during the local winter months. The greater amplitude of the pulsations, which are thought to modulate the ELF/VLF emissions and thus produce the QPs, might thus increase the modulation of these emissions and make it more likely that they would be observed at all the available stations.

[27] The very few QP 2 emissions observed (Figure 3b) were also restricted to near local noon. Their diurnal distribution was similar at all four stations and, as noted above, there was no seasonal or latitudinal variation in their occurrence.

[28] Figure 3c (middle panel) shows, in contrast, that periodic emissions could occur throughout the day and night, but there were ~60% more occurrences during postnoon and evening hours than during nighttime and prenoon hours. There was also a clear latitudinal depen-

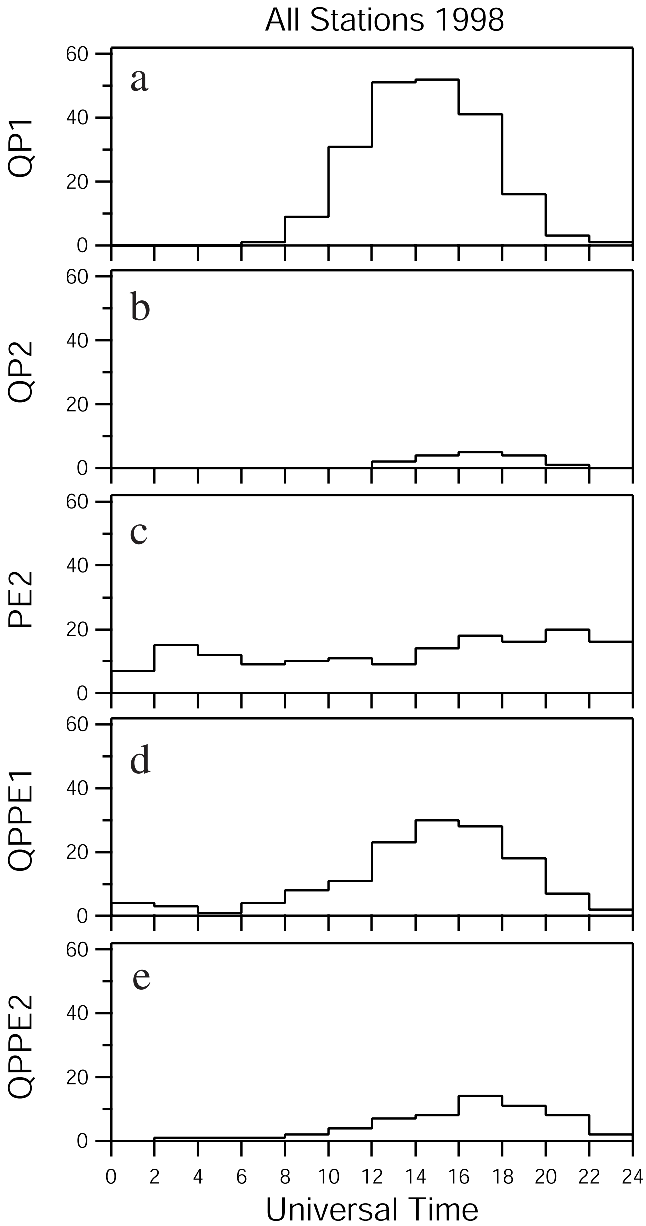

Figure 3. Diurnal occurrence patterns (in 2-hour intervals) of "all-station" modulated ELF/VLF emissions in the QP 1, QP 2, PE 2, QPPE 1, and QPPE 2 categories during 1998. Local magnetic noon is at ~1500 UT.

dence in both occurrence (as noted earlier) and in diurnal distribution (Figure 4). At Halley there was a minimum in PE occurrence near local noon, and at A80 only a slight local noon minimum. In contrast, strong noon/early afternoon maxima were evident at A81 and South Pole, and not a single nighttime PE event appeared at South Pole. Because of the higher occurrence rate at Halley, the "all-station" pattern in Figure 3c shows little trend other than a broad afternoon-evening maximum.

[29] The latitudinal differences in diurnal occurrences shown in Figure 4 might be explained in terms of the ionospheric conditions above each station. The PE occurrence is strongly weighted to austral winter. At the highest latitude stations in winter, the ionosphere is dark at noon so absorption of downcoming magnetospheric waves is low. At Halley, on the other hand, although sunlight does not reach the ground at noon midwinter (Halley is well south of the Antarctic Circle), it does illuminate the ionosphere at 100 km altitude, typical of the height where wave absorption occurs. This will affect not just the transmission to the ground receiver but also the echoing efficiency. This effect then may more than cancel the dayside tendency that dominates at the higher latitudes.

[30] Figures 3d and 3e (fourth and fifth panels) show that QPPE 1 and QPPE 2 events could occur at any local time. As with the QP 1 and QP 2 categories, however, the distributions peaked near local noon, with the center of the QPPE 1 distribution appearing approximately three hours before that of the QPPE 2 distribution. The local time distribution for these wave categories was again essentially the same at each station, and in both summer and winter.

[31] In summary, the distribution of all categories of QP events peaked on the day side, as found earlier by *Ho* [1973] and *Morrison et al.* [1994], while the distribution of PE events without simultaneous QP emissions was strongly

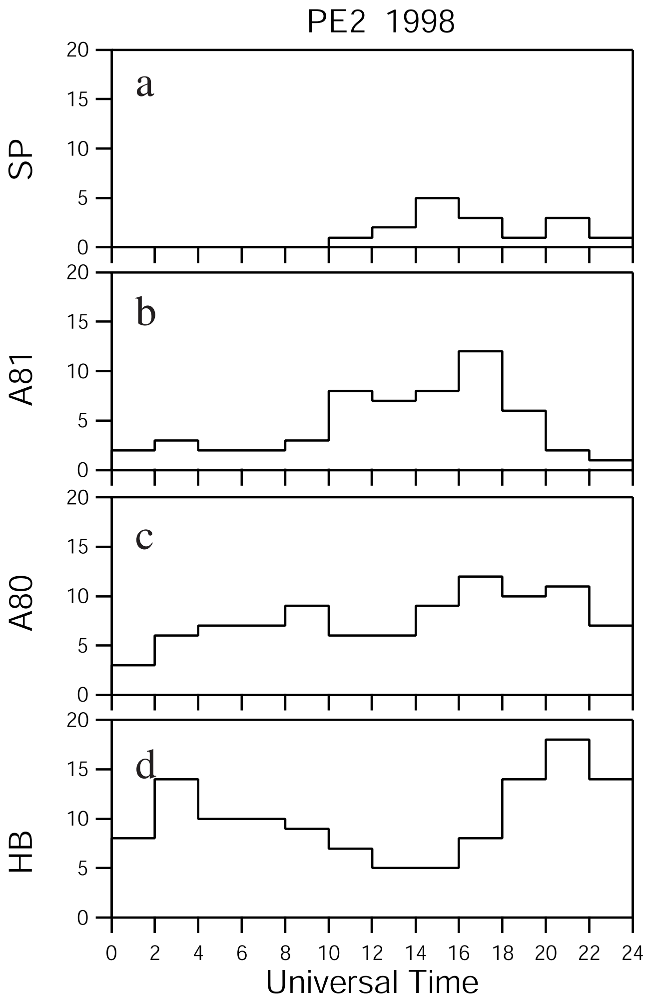

Figure 4. Diurnal occurrence patterns of PE events at South Pole (SP), BAS AGO A81, BAS AGO A80, and Halley during 1998.

Table 4. K_p Indices for 31 July and 1 August 1999

	Time of Day							
	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
31 July	4+	4+	4+	2–	2	3–	5–	4+
1 August	4+	3	1+	1	1–	1	0	0+

latitude-dependent, with most occurring at subauroral latitudes in a pattern having a minimum in occurrence near local noon.

4. Case Study: The PE 2/QPPE 2 Event of 1 August 1999

[32] An unusually intense and sustained interval of PE activity, and somewhat later of type 2 QP activity, occurred from 2000 UT 1 August 1999 through 0130 UT 2 August 1999. Wideband synoptic data were available from Halley throughout the day, and from South Pole after 2200 UT, and will be used in conjunction with time series data from these stations as well as from AGOs A80 and A84 to provide a detailed overview of the VLF activity during this event.

[33] Geomagnetic activity had been high (K_p up to 5-) in the preceding 24 hours (Table 4) but became very quiet ($K_p \leq 1$) during the last half of the day. Such conditions are favorable for whistler mode activity in general and periodic emissions in particular, because of the stable propagation and echoing conditions in an expanded plasmasphere (whistler echoes are rarely if ever observed to propagate outside the plasmapause) combined with the elevated energetic electron fluxes necessary for wave generation still persisting from the previous day's activity.

[34] Both time series and wideband data indicated that over the entire duration of this event there was very little power (and hence very little modulation was evident) at any of the four stations at frequencies below 1.5 kHz. In general, whistlers were observed with frequencies ranging from a minimum of 2–3 kHz up to a maximum of 6–8 kHz, but PE and QP modulations were usually limited to the 1.5–3 kHz range.

[35] Figure 5 shows a Fourier spectrogram of 0–500 mHz modulations of VLF signals from all four stations for a 4-hour interval (2000–2400 UT) on 1 August 1999. The upper panel shows the 1–2 kHz channel from South Pole, and the lower three panels the 2 kHz channels from A84, A80, and Halley, respectively. In each panel the intensity of the modulations is color-coded (in arbitrary but uniform units) as a function of frequency (vertical axis) and time (horizontal axis).

[36] Figure 5 indicates the presence of a sustained first harmonic PE with frequency f_1 slowly rising from 260 to ~290 mHz, and an (aliased) second harmonic PE with frequency $f_2 = 2(f_{\rm Nyquist} - f_1)$, where $f_{\rm Nyquist} = 500$ mHz, falling from 480 to 420 mHz, from ~2100 until at least 2400 UT. The figure shows the gradual appearance of a QP beginning shortly after 2200 UT. Magnetometer data from South Pole station (not shown) indicated strong Pc3 signals from 1000 UT to ~1650 UT, with greatly reduced power until 2030, but with no observable enhancement above background levels the remainder of the day, so we classify this as a QPPE 2 event. Figure 5 shows a gradual increase in the QP frequency as well. The gradual increases in frequency in both QP and PE emissions are probably due to either decreasing density [cf. *Smith et al.*, 1998, where a similar decrease is seen in late morning], or to the motion of ducts, because the frequency of the modulated signals at each of the four stations remained identical.

[37] Whistlers first appeared on this day near 1100 UT, from 6 kHz down to 3 kHz, with occasional signals in the 2 kHz channels as well. Impulsive activity in the 2 kHz channel increased after 1400 UT, but was largely independent of the higher frequency whistler activity. Occurrences of impulsive activity in both frequency ranges gradually became more frequent toward the end of the day, but with the exception of the subset of whistlers with (usually attenuated) power below 2.5 kHz, they were temporally independent.

[38] The first instances of echoing occurred after 1800 UT in the 2 kHz channel, but persistent PE activity was observed only after 2030 UT. By 2120 UT large amplitude PEs and impulsive events appeared independently near 2 kHz, although many of the largest amplitude impulsive events appeared to cut off PE activity, as noted earlier by *Ho* [1973]. This is evidence that at least one strong component of the whistler is propagating on the same path as the PE. Such interactions between co-propagating whistler mode signals are not uncommon [*Park*, 1977], and have been well demonstrated with artificial signals from the Siple transmitter [*Helliwell*, 1987, 1988].

[39] Figure 6 shows a 10-min sample of this four-station data set from 2120 to 2130 UT, indicating the impulsive nature of the 2-kHz channel's time series early in this event. Of the large-amplitude spikes evident, e.g., near 2122:15, 2122:48, 2123:50, and 2129:25, only the third can be identified as a whistler, because it occurred simultaneously in higher frequency channels not shown (e.g., the 3 kHz, 4.25 kHz, and 6 kHz channels at Halley). By contrast, several large-amplitude whistlers evident in the higher frequency channels during this interval produced neither impulsive activity nor changes in PE activity in the 2 kHz channel. PEs with ~4-s repetition rate occurred repeatedly, but were often temporarily suppressed by strong impulsive (but not whistler-related) activity, as for example the strong signals at 2127:30 and 2129:30 UT. Both the whistlers and the PEs were most intense at A84. A80 had the next largest amplitude PEs, with smaller values at Halley and South Pole, suggesting that the PEs propagated on a path with a footprint lying between the latitudes of A84 and A80 (but closer to the former). The situation is less clear for the whistlers because the first hop whistler will probably contain components that have traveled on several paths with a range of *L*-shells and longitudes. (In Figure 8b, whistler components are seen at Halley passing through the 1 kHz band of very high waveguide attenuation, and their path must therefore be close to Halley.)

[40] A transition occurred near 2220 UT, as peaks in power became more nearly periodic (at QP frequencies). It is at this time that a well-defined QP frequency first appeared in Figure 5. PE activity still often increased from power minima after large peaks, but at times was now sustained through both maxima and minima. By 2250 UT PE levels were roughly uniform, and rode on large, packet-like series of QP maxima. After 2300 UT the largest QP packets still appeared to deplete the total wave power in

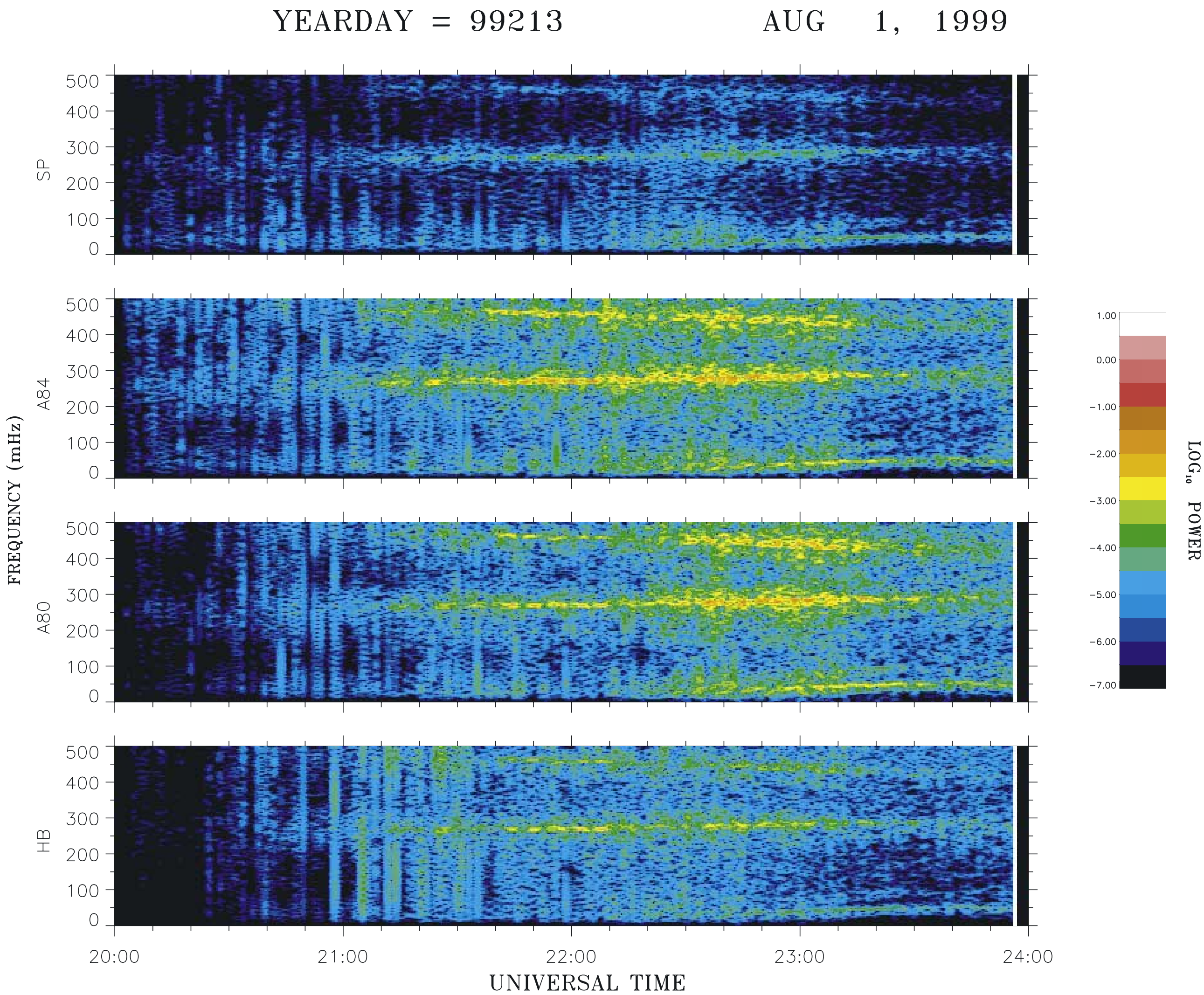

Figure 5. Fourier spectrogram of 0–500 mHz modulations of VLF signals at four Antarctic stations from 2000 to 2400 UT 1 August 1999. From top to bottom the panels show the 1–2 kHz channel from South Pole Station (SP) and the 2 kHz channels from A84, A80, and Halley, respectively. The frequency of modulations is shown on the vertical axis, and the intensity (in arbitrary units, the same for each station) is color-coded.

their aftermath, causing a steep drop in PE amplitude, while the smaller ones did not. QP and PE power were both steady from 2320 to 2330 UT, but the interval from 2350 to 2400 UT showed the same behavior noted above for 2300–2310 UT.

[41] Figure 7, showing a 10-min sample from 2320 to 2330 UT, shows this later pattern: Although PEs are still present, sustained QP emissions dominate the signal at all stations, and small local differences are evident as well. Approximately one whistler per minute appeared in the 6-kHz channel at Halley during this time, but again reached down to only ~3 kHz; they seemed to have no effect on the QP and PE signals in the 2-kHz band.

[42] It has long been known that Pc3 magnetic pulsation trains typically consist of multiple wave packets that have random phases relative to each other, resulting in abrupt phase shifts in ground magnetometer data. Although no abrupt phase shifts are evident in the QP emissions shown in Figure 7, such phase shifts were observed during most portions of the interval from ~2230 to 2400 UT when QP emissions were clearly present. *Ho* [1973] reported such phase shifts associated with whistlers. The QP emissions also show a gradual increase in frequency, which is evident, both in Figure 5 as a slowly rising band of enhanced power, and in Figure 7 as a gradual decrease in repetition period. Coupled with the fact that the QP signal is in phase at all four stations, these characteristics suggest that the signals at all four stations originate at one location. The steadily increasing modulation frequency in both the QPs and PEs simultaneously is probably due to a decreasing plasmaspheric density as the stations move from the bulge region toward midnight. It is similar to but in the opposite direction from the decreasing frequency of morning events found by *Smith et al.* [1998] and attributed to increasing plasmaspheric density.

[43] Figure 8 shows simultaneous wideband data from Halley and South Pole. In each panel one minute of ELF/VLF power is shown in spectrogram format from 0 to

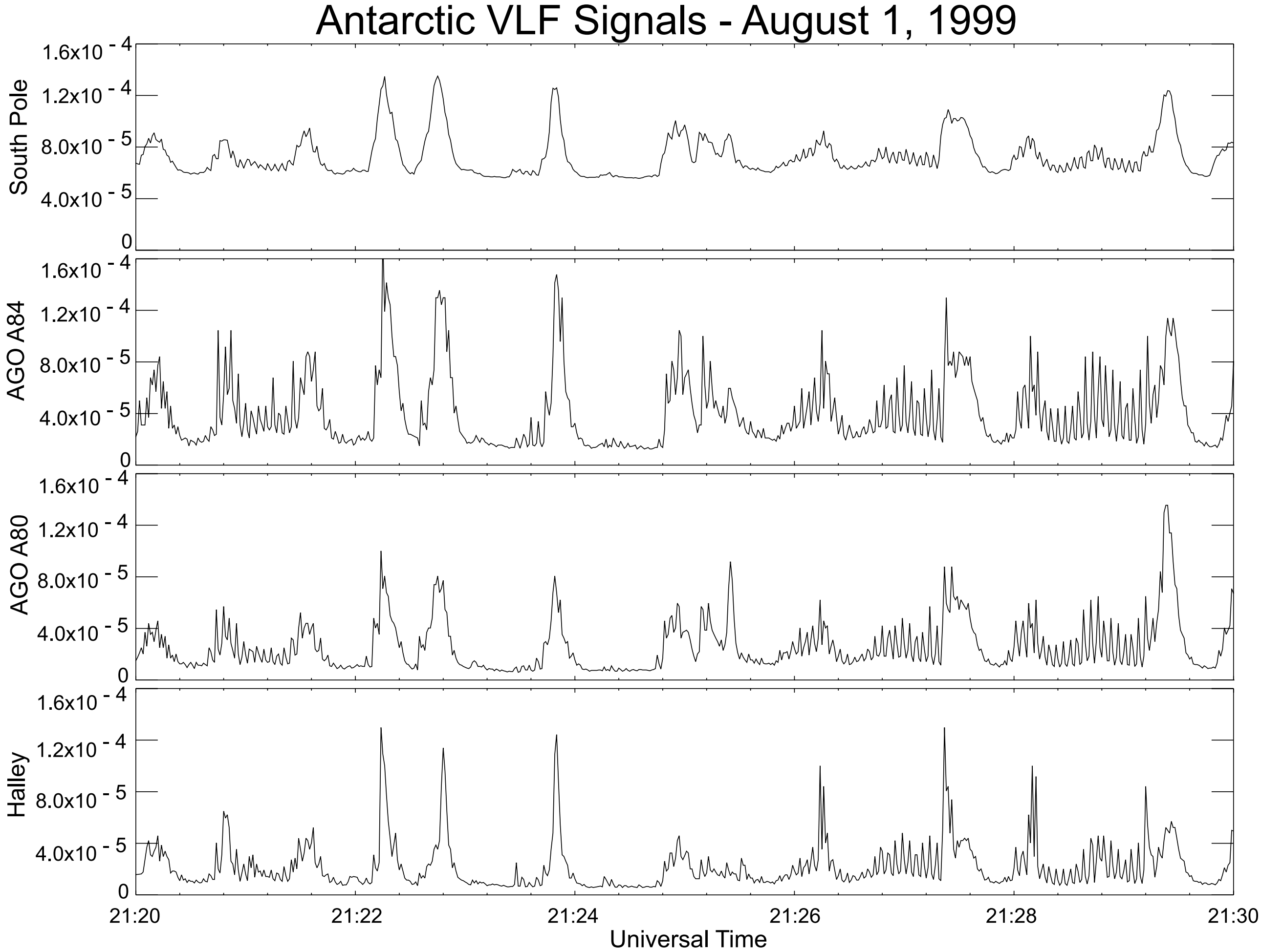

Figure 6. Plot of signals in the 1–2 kHz channel from South Pole Station and the 2 kHz channels from A84, A80, and Halley, respectively, in V/m, from 2120 to 2130 UT 1 August 1999.

5 kHz, color-coded in dB according to their respective color bars.

[44] Figure 8a shows nearly identical PE emissions throughout the interval from 2205 to 2206 UT (note the data gap from 0 to 1.3 s in the Halley data). Two strong multihop whistlers are evident at Halley near 2205:25 and 2205:45 but only the first hop is evident, much weaker, at South Pole. Presumably some relatively high latitude components in the first hop are close enough to be seen at South Pole but the echoing path is too distant. Other, more sustained emissions near 4 kHz, most probably outside the plasmasphere, are evident at South Pole but not at Halley. Some apparently triggered emissions are evident at both stations in the aftermath of the two whistlers, but it is not clear whether they are causally related. The detailed similarity of the PE emissions seen in these two wideband spectrograms suggests that power from one source has propagated to both receivers. The two-hop whistler echo time at Halley is similar to that of the PE (~3.7s at 2.2 kHz), so they could be echoing on the same path, which would therefore be closer to Halley than to South Pole.

[45] Figure 8b shows quite a different structure from 2220 to 2221 UT, with the appearance of a packet-like QP structure. At Halley, two PE trains, with a phase separation of nearly 180°, are grouped together in a packet from 2220:10 to nearly 2220:40. Two multiple-hop whistlers, the second stronger, appear at 2220:45 and 2220:52, respectively, and in this case appear to strengthen one of the PE trains and may also be related to the triggered emissions beginning near 2220:54. A similar QP-like wave packet appears at SP, but the individual PE structures are much less distinct. Steady higher-frequency emissions are again evident near 3 and 4 kHz, and broadband emissions above 3 kHz begin at the time of the two whistlers, at 2220:45 and 2220:52 (these are probably unrelated to the PEs and occur outside the plasmapause). Here, too, one of the PE trains appears to be strengthened after the appearance of the whistlers.

[46] By 2235 UT, the beginning of the 1-min interval shown in Figure 8c, the transition to QP structure is nearly complete. The first of the two wave packets shown in this interval at both Halley and South Pole more clearly exhibits PE-like temporal structure (1–3 s period), but only very weak signals continue the PE periodicity between 2235:30 and 2235:35 at either station. The QP generation process has taken over from the PE. Multihop whistlers again appear at Halley at 2235:08, 2235:17, 2235:44, and 2235:53 (with only one-hop signals evident at South Pole), but do not appear to perturb the ongoing QP activity. Note that only in the case of the second of

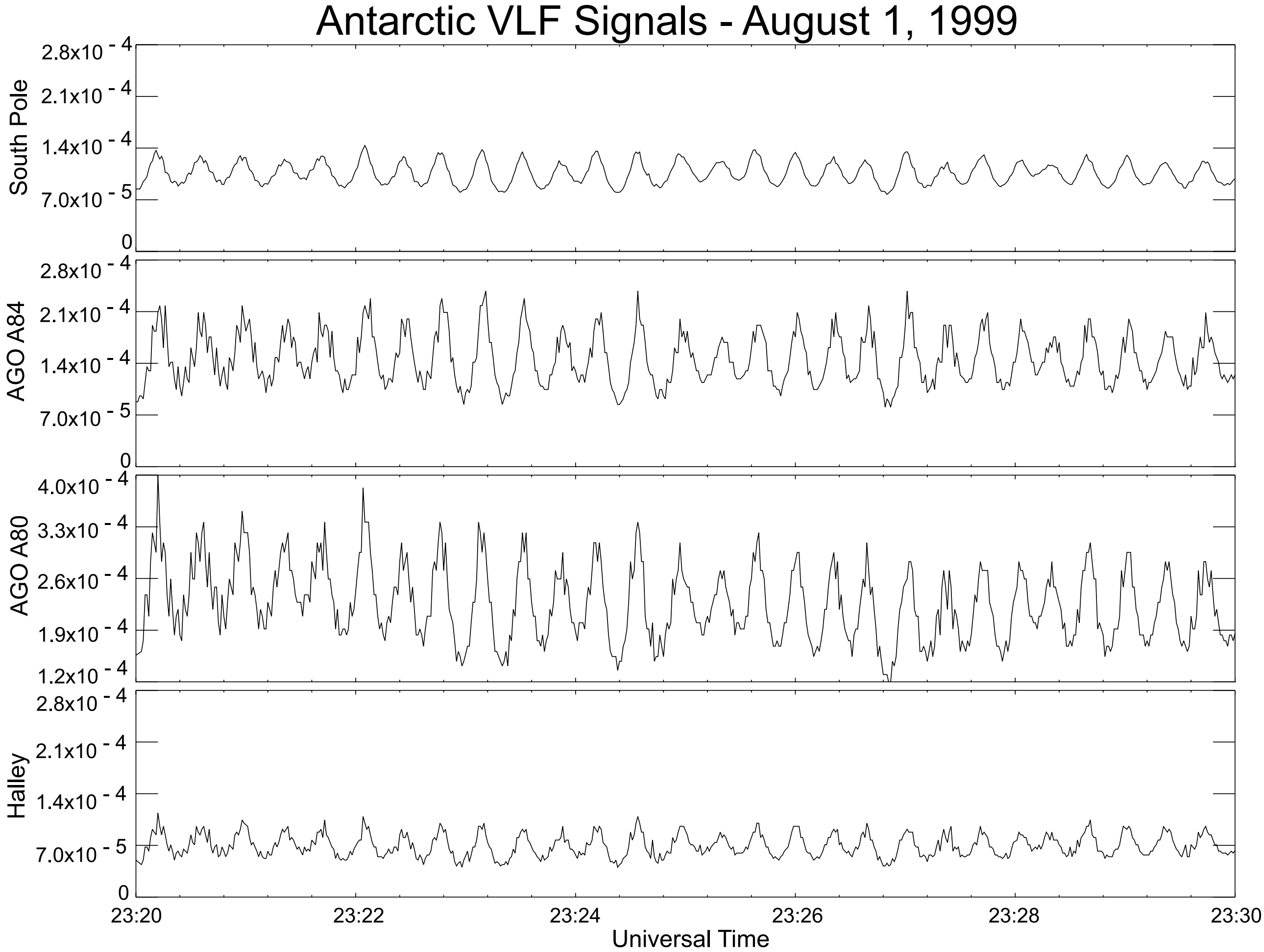

Figure 7. Plot of signals in the 1–2 kHz channel from South Pole Station and the 2 kHz channels from A84, A80, and Halley, respectively, in V/m, from 2320 to 2330 UT 1 August 1999. Note that although all panels are plotted to the same scale, the AGO A80 data are offset.

these whistlers is power evident below 1.8 kHz, and even then only in significantly attenuated form. The second QP packet in this interval exhibits significant power down to 1.3 kHz at both Halley and South Pole. This lack of a similar frequency boundary again suggests that the whistler is generated on a flux tube more distant from these stations.

[47] PE structure returned intermittently, however. Figure 8d, covering the interval from 2250 to 2251 UT, shows both QP and PE structure at both stations, with relatively weak PE activity also evident between 1.4 and 1.8 kHz. The temporal pattern is similar to that of Figure 8b, but with the addition of these lower frequency PEs. Again two whistlers (the stronger at 2250:30 and the weaker at 2250:44) have only minor effects on the repetitive emissions. By 2305 and 2320 UT (not shown), the QP repetition period had decreased to less than 30 s and the background power level at and slightly above 2 kHz continued to increase, but little else had changed. The QP and PE emissions continued after 2400 UT but did not significantly change their character. They gradually faded and disappeared by 0130 UT of the following day, 2 August 1999. Whistlers, however, continued intermittently at South Pole even after the QP and PE emissions disappeared.

[48] The drop in PE amplitude after 2300 evident in Figure 5 may be more apparent than real. Both the time series data shown in Figure 7 and the wideband data shown in Figure 8 indicate that although there was perhaps a slight decrease in PE amplitude late in the day, the most prominent change was that the power did not drop to as low a level during relative minima. This could reflect the development of multiple paths, or superposing ducts, with slightly different resulting echo periods. It is clear, however, that the primary modulation frequency observed at each of the stations remained identical at each station throughout the duration of the event.

5. Discussion

[49] Comparison of occurrences of QP and PE events at latitudes from the subauroral zone to the cusp indicates substantial differences in occurrence rates, but only in the case of PEs do they indicate significantly different diurnal behavior. QP events of all categories were most often seen in the auroral zone, while PE events occurred much more frequently at Halley, at subauroral latitudes. At all four stations the seasonal patterns for each category were similar. This similarity in occurrence across substantial

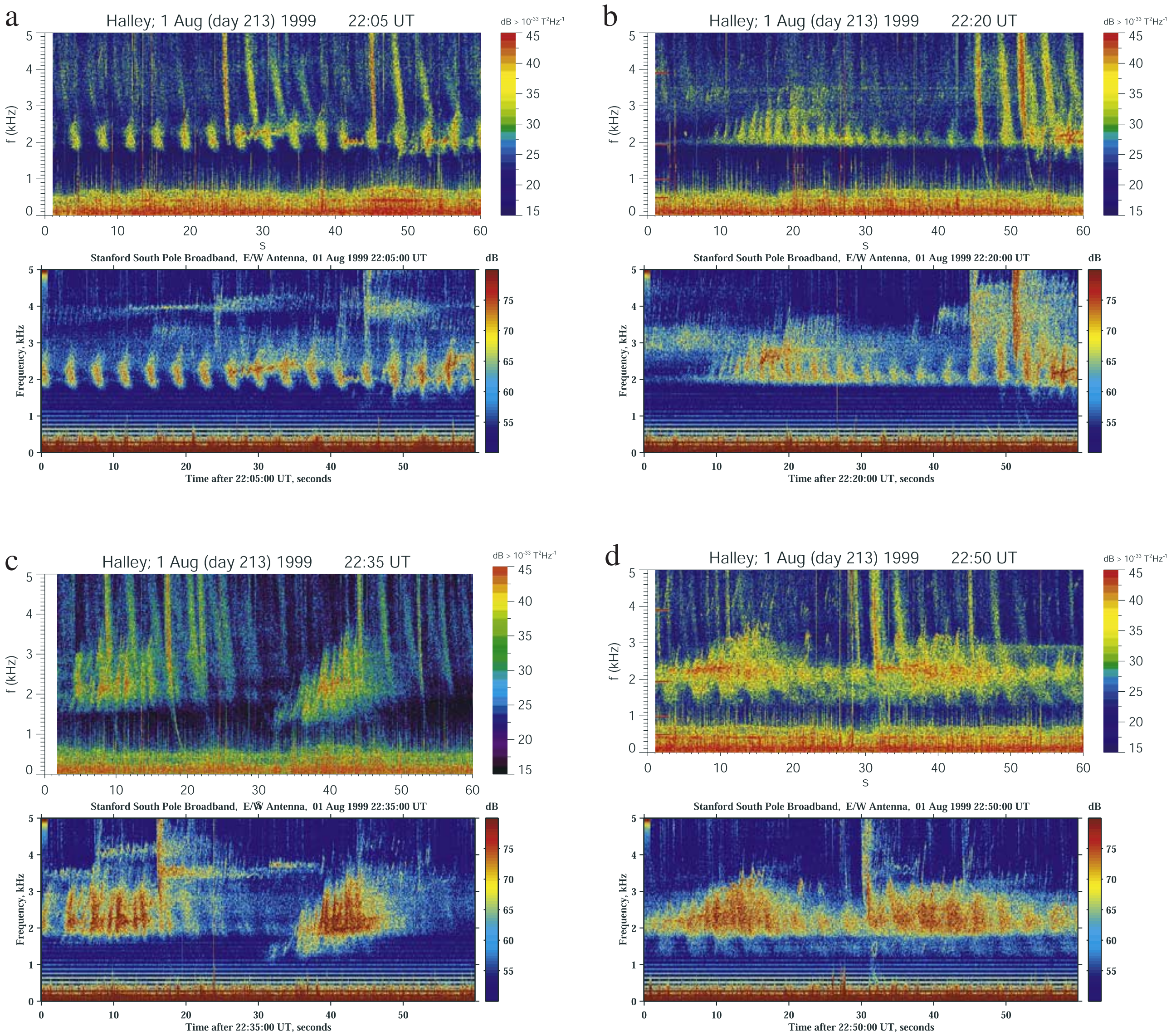

Figure 8. Wideband VLF snapshots of 0–5 kHz wave power from Halley (upper) and South Pole (lower) for four 1-min intervals on 1 August 1999: (a) 2205–2206 UT, (b) 2220–2221 UT, (c) 2235–2236 UT, and (d) 2250–2251 UT. In each case the frequency is shown on the vertical axis, and the intensity is color-coded according to the color bar for each respective station.

distances is consistent with the fact that most events were observed at two or more stations, thus making meaningful a compilation of "all-station" events.

5.1. Simultaneity and Latitudinal Range

[50] A comparison of ELF-VLF observations from the roughly conjugate sites Syowa, Antarctica and Husafell, Iceland [*Sato and Kokubun*, 1980] showed that individual type I QP elements occurred at both sites simultaneously within an accuracy of 1 s. They contrasted the good conjugacy between these two stations, with $\Delta L \sim 0.2$, to earlier negative results of a conjugate investigation by *Kitamura et al.* [1969], who noted a lack of conjugacy between Great Whale River (Canada) and Byrd (Antarctica), separated by a ΔL of 3.7. *Sato and Kokubun* [1980] interpreted this symmetry in timing between conjugate hemispheres to indicate that the interaction between whistler mode waves and hydromagnetic waves occurs near the equator in the outer magnetosphere. They also suggested that compressional mode pulsations were the cause of the type I QP emissions.

[51] As noted above, *Morrison et al.* [1994] presented one case in which strong type I QP signals were in phase at three widely separated locations in Antarctica (Halley, South Pole, and Siple, each ~1000 km distant from the others, and with $\Delta L \sim 9$) while the simultaneously observed Pc3 magnetic signals showed no coherence between stations. Detailed study of the 1 August 1999 event and many others from 1996 through 1999 revealed that in every case when QP or PE emissions were evident at two or more stations, these occurred simultaneously to within the 1-s time resolution of the samples. (There was an apparent time shift of 1 ± 0.5 seconds between South Pole and the BAS sites, but the different sampling and

time-stamping procedures at the U.S. and BAS stations appeared to account fully for this shift.)

[52] This confirmation of the simultaneity of most if not all QP and PE events lends support to the idea advanced by *Morrison et al.* [1994] that each site is seeing a signal from the same relatively localized, ducted whistler event in the magnetosphere. The range of latitudes available in this study thus gives us clues about the *L*-shells on which these events originate. The location of these preferred regions is also suggested by other recent studies [*Fung et al.*, 2003; *Carpenter et al.*, 2002] that used Radio Plasma Imager data from the IMAGE satellite to characterize small-scale field-aligned density structures (ducts). The RPI data imply a range of cross-field scales in the outer plasmasphere and plasmapause of ~0.25–2 km. A much earlier study using data from the SCATHA satellite by *Koons and Roeder* [1990] also suggested that the satellite was most likely within the plasmasphere each time whistlers were detected.

[53] Although it is likely that these emissions are generated in, and propagate along, a particular duct, our observation of essentially identical signals at great distances suggests that when the signals penetrate the ionosphere at the base of the duct, they begin to propagate within the Earth/ionosphere waveguide. Thus stations nearest the ionosphere exit point would receive a stronger signal and stations further away (presumably at higher latitudes) would receive a signal of reduced strength. If this interpretation is correct, then the relative intensities shown in Figures 6 and 7 suggest that, at least on 1 August 1999, the relevant duct was located near the latitude of A80 and/or A81, near 67° magnetic latitude.

[54] A study of several QP events simultaneously observed in space and on the ground by *Sato et al.* [1981] provides additional important information in this context. *Sato et al.* [1981] presented simultaneous observations of QPs from the polar-orbiting ISIS 1 and 2 satellites and from Syowa Station, Antarctica (−70° MLAT). Both ISIS 2, in a 1400-km circular orbit, and ISIS 1, in an elliptical orbit with 3520 km apogee and 570 km perigee, were at altitudes above the Earth-ionosphere waveguide. *Sato et al.* [1981] found a one-to-one correspondence between most individual QP intensifications in space and on the ground for six orbits out of 273 obtained from May 1976 to January 1979. Of these, five were type I QP events and one was a type II QP event. During these six events the ISIS satellites were located between ~−54° and ~−78° MLAT and within ~2 hours MLT of the ground station. That is to say, the QP emissions were observed simultaneously over a range of latitudes, extending from near the open/closed field line boundary to equatorward of the nominal auroral zone.

[55] This satellite-ground study's observations are consistent with the observations reported here in showing the wide latitudinal range of simultaneous QP modulations. However, the most straightforward interpretation of the *Sato et al.* [1981] observations would be that simultaneous, downgoing QP emissions exist over a wide latitudinal range in the lower magnetosphere/topside ionosphere before they penetrate into the lower ionosphere and propagate through the Earth-ionosphere waveguide. They would thus serve as evidence against a localized source such as an individual duct.

[56] We might expect type I QPs to be similar over a wide range of L and MLT, both on the ground and in space, if they are driven by compressional Pc3-4 waves which are similarly large scale phenomena. However, we would not expect this to be the case if type II QPs are driven by PEs as suggested by *Smith et al.* [1998]. This is because the PEs by their very echoing nature are assumed to be on a localized field-aligned path.

[57] Some of the details reported by *Sato et al.* [1981] for the one type II QP event they observed, however, help us to formulate an alternate interpretation of their observations. First, the type II QP event presented by *Sato et al.* [1981] was not observed at ISIS-1 when the satellite was at the same magnetic latitude as Syowa, but only at lower magnetic latitudes (from −66° to −54° MLAT). We suggest that their satellite observations might indeed have been centered near the origin of the type II QP event and had good propagation to Syowa, but that the spread over ±5 degrees of latitude (about ±550 km) should be explained by the upward non-ducted and thus non-localized reflection of downcoming ducted wave energy. The available satellite data apparently do not provide information on the direction of their propagation, and without satellite wave vector measurements, distinguishing between these two alternatives would not be possible.

[58] A detailed examination of Figure 7 of *Sato et al.* [1981] in fact reveals other information consistent with our interpretation. Three whistlers and a hiss band were also observed during this interval at Syowa, but none these were evident at ISIS-1. *Sato et al.* [1981] interpreted this as indicating that the whistlers and hiss band (which during this event appeared at frequencies higher than that of the QPs) were generated in regions different from the source region of QP emissions. We note that PE structure is evident within the QPs near 2012 UT in both the ISIS-1 and Syowa data, and that its frequency is somewhat lower than that of the echoing whistlers observed at 2002, 2007, and 2014 UT in the Syowa data. This is consistent with the occurrence of both PE and QP emissions together at a higher L shell than that of the whistlers and their echoes that were seen only at Syowa.

5.2. Relation of QP and PE Events to Whistlers

[59] The wideband observations during the 1 August 1999 event support the idea that the observed whistlers typically propagated on L shells near or even below that of Halley (L = 4.2), but their apparent typical lack of influence on QP and PE events may suggest that these latter occurred at higher L values. The fact that maxima in both occurrence over the year and in amplitude on 1 August 1999 were seen at A80 or A81 rather than at Halley is also supportive of this suggestion. Given the very quiet geomagnetic conditions on this day (0 and 0+) at the time of the event, it is reasonable that these stations were beneath the outer plasmasphere, and thus under regions of such small-scale density structures.

[60] If the conditions favorable to the occurrence of PEs are the same as those favorable for the occurrence of multihop whistlers, then their annual variation might be

due to variations in whistler production. Relevant here are the observations of *Koons and Roeder* [1990], who found in their survey of ELF/VLF activity observed by the SCATHA satellite that the relatively few lightning-generated whistlers present in this data set were predominantly detected during the northern hemisphere summer season. On the other hand, the 1 August 1999 event reveals a relatively tenuous connection between individual whistlers and PEs, and ionospheric absorption is at its lowest value in the southern ionosphere in June because of the 24-hour dark conditions (although as noted above this is only marginally true at Halley), so the April-September maximum might be primarily due to propagation effects.

5.3. Generation Mechanisms

[61] The near-noon peak in the diurnal profile of QP 1 and QPPE 1 events is consistent with the observations of *Morrison et al.* [1994], again supporting the commonly held view that Pc3-4 magnetic pulsations are the driver of the observed modulations of ELF/VLF waves (type I QPs). As *Smith et al.* [1998] noted, however, the generation of type II QP events is not well understood. One possibility suggested by *Sato and Kokubun* [1981] was that the modulation agent for type II QP emissions is a localized magnetic pulsation that is not observable on the ground.

[62] *Smith et al.* [1998] had presented a qualitative model, based on the earlier work of *Bell* [1976] and *Sato and Matsudo* [1986], by which PEs could generate QPs. In this model (shown in their Figure 5) strong nonlinear amplification of whistler mode waves in a spatially confined field-aligned duct would scatter electrons into the loss cone. This process could drive highly localized field-aligned currents which generate Alfven waves that then set up a ULF resonance on the flux tube of the whistler duct. *Smith et al.* [1998] suggested that the highly localized nature of these ducts and of the consequently driven ULF pulsations would make them only marginally detectable on the ground.

[63] The fact that both QPPE 1 and QPPE 2 events can occur at any local time is consistent with their generation by PEs, but of course cannot verify it. The extended event of 1 August 1999 provides an example of the transition from impulsive events, to a long-lasting PE, and then to a QPPE 2. Even with the wideband data available for this event, however, the detailed energy pathway that might generate the QPs is not evident. Further, our observations that QPPE 1 and QPPE 2 events also peak on the day side, while PEs do not do so, suggest that even if the above mechanism is valid, the conditions under which it might be able to generate localized magnetic pulsations in the equatorial amplification region might be somewhat restricted.

[64] The near-noon localization of the few QP2 events seen in this study, and the absence of even one PE 1 event, may provide additional dimensions to this search for generation mechanisms. The total absence of PE 1 events in our statistical study is perhaps surprising: a simple overlapping of independent distributions of PEs and magnetic pulsations might suggest that there should be a modest number of such events. Instead, we suggest that when echoing conditions are such as to produce PEs, the presence of Pc3-4 pulsations might necessarily drive QPs as well, with the result that such an event would fall into the relatively common QPPE 1 category. This might explain the daytime peak in QPPE 1 events.

[65] *Smith et al.* [1998] implicitly assumed that their mechanism would set up transverse field line resonances, the most common type of Pc3-4 pulsations observed. Theoretical considerations, however, would suggest that compressional pulsations would be more effective in modulating ELF-VLF emissions (e.g., as pointed out by *Sato and Kokubun* [1980]). *Engebretson et al.* [1987] noted that both transverse field line resonant and compressional Pc3-4 waves were typically set up in association with radial IMF conditions. In addition, *Takahashi and Anderson* [1992], in their analysis of AMPTE CCE magnetometer data in the region between $L = 2.5$ and 6.5, observed at times an additional class of purely compressional dayside Pc3 pulsations that appeared to be localized near the magnetic equator, near noon, and near the nominal plasmapause, which is also the supposed region of nonlinear whistler amplification. Our recent studies of magnetometer data from the Cluster II satellites have revealed examples of similar dayside, equatorially localized Pc3-4 waves near $L = 4.4$, and in at least one case of purely compressional Pc3-4 wave activity at the equator, there was no evidence in ground magnetometers of simultaneous pulsation activity [*Engebretson et al.*, 2003; M. Engebretson et al., manuscript in preparation, 2004]. Our observations that every one of the QP2 events occurred on the day side, with the peak within two hours of local noon, and that QPPE 2 events also have a day side peak, are quite consistent with this possibility. We intend to pursue the possible connection between compressional Pc3 events and QP2 emissions in future studies.

6. Summary and Conclusions

[66] Our survey of two years of QP and PE emissions and associated Pc3-4 magnetic pulsations has extended the results of several earlier studies (including *Ho* [1973], *Morrison et al.* [1994], and *Smith et al.* [1998]), providing more extensive data both regarding diurnal and seasonal variations, and on the interactions between these two kinds of modulated emissions.

[67] 1. Comparison of calibrated amplitudes shows that QP events both with and without magnetic pulsations occur more frequently in the auroral zone (near the latitude of AGO A80) than at either higher or lower latitudes, while the occurrence of PE events increases monotonically with decreasing latitude (down to 62° MLAT).

[68] 2. QP and PE events show opposite seasonal variations, with QPs most common in austral summer and PEs most common in austral winter. Events during which both QPs and PEs appear simultaneously occur more evenly throughout the year.

[69] 3. Diurnal patterns of all categories of QP events show maxima in the noon or post-noon sectors. The total absence of QP 1 occurrences on the nightside is consistent with the expected absence of Pc3-4 pulsations there, because of their origin at the upstream bow shock. Diurnal profiles showed no latitudinal or seasonal differences for most categories, except

for a clear reversal of the profile of PE occurrence with latitude. This may be related to the latitude-dependent solar illumination of the winter dayside ionosphere, which exerts significant control over its conductivity.

[70] 4. In every multistation event studied, we have found QP and/or PE modulations to be simultaneous at all stations to within the 1-s sampling time of the data. This suggests that all such events originate in a single, localized region, most probably near the plasmapause. When frequency variations of QPs and PEs are observed, they are often downward in prenoon hours [*Smith et al.*, 1998] and upward at dusk (as in the 1 August 1999 event). Both trends are consistent with the well-known increase and decrease of plasma densities along the wave propagation paths from dawn through dusk.

[71] 5. Type II QPs are strongly associated with PEs, confirming the observations of *Smith et al.* [1998] who first noted this link. The event of 1 August 1999 shows an example of this association, and also of the complex relations between whistlers and these periodic modulations. Although the wideband data does not give clear evidence that PEs are directly driven by echoing whistlers, it does suggest that strong echoing is a necessary condition for the development of PEs.

[72] Although the fraction of QP events associated with PEs is considerably lower in this study than in that of *Smith et al.* [1998], we believe this may be due to the more stringent event identification criteria we used. This may also explain why *Smith et al.* [1998] found no QP 2 events, whereas in the current study these were observed with a (still low) occurrence rate of 3–4%.

[73] 6. Our observations are consistent with the process outlined by *Smith et al.* [1998] by which PEs can lead to the generation of QPs, and the absence of PE 1 events can arguably be related to the effectiveness of this mechanism. In addition, we have noted that the small number of QP 2 events we have observed is tightly clustered near local noon. The existence of a set of equatorially localized, near-noon, compressional Pc3-4 waves that evidently do not appear in ground records suggests that this category as well might be generated by ULF wave modulation of equatorial ELF/VLF wave growth. Although we believe that such a process may be able to explain the origin of most if not all type II QPs, further observational studies combining ground and satellite data sets will be needed to test this or other models in detail.

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