VLF WAVE ACTIVITY DURING A MAGNETIC STORM: A CASE STUDY OF THE ROLE OF POWER LINE RADIATION

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Abstract. Ground-based data on magnetospheric wave activity in the American longitude sector are studied for a 13-day period that includes a major magnetic storm and some isolated substorm activity. The wave intensity in the 0.5- to 10- kHz range shows clear association with geomagnetic activity. A detailed examination of VLF spectra shows that the strongest waves emerging from the middle magnetosphere during the storm recovery period and during isolated substorm activity are often emissions stimulated by radiation from the electrical power distribution system. Several different types of power line radiation effects are illustrated by using broadband spectral data from stations in Antarctica and North America. It appears that man-made VLF noise has a strong influence on the energetic particle population in the magnetosphere.

Introduction

Helliwell et al. [1975] reported evidence that harmonic radiation from the 60-Hz power system in eastern Canada leaks into the magnetosphere with sufficient intensity to stimulate strong whistler mode instability. When weak but coherent signals enter the wave-particle interaction region near the equator, they can be greatly amplified and trigger emissions in an otherwise quiescent magnetosphere. Such effects have been clearly demonstrated by controlled wave injection experiments at Siple, Antarctica [Helliwell and Katsufrakis, 1974]. In these experiments, triggered emissions were found to be typically ~30 dB above the input signal strength [Helliwell and Katsufrakis, 1974; Stiles and Helliwell, 1977].

The above results raise important questions regarding the role of coherent man-made signals in magnetospheric wave activity and consequent effects on energetic particle dynamics. Ground-based observations indicate that under certain conditions, power-line-induced emissions are the strongest VLF waves emerging from the middle magnetosphere [Helliwell et al., 1975; Park, 1976]. A low-altitude (~500 km) satellite survey by Bullough et al. [1976] revealed a strong peak in VLF wave activity over North America ($2 < L < 3$), which the authors attributed in part to power-line-induced emissions. Luette et al. [1977] examined the geographical distribution of chorus activity at high L values ($4 < L < 10$) observed by the Ogo 3 satellite and found that significant peaks in activity could be traced to major industrial areas of the world.

Although there are indications that power line radiation (PLR) plays a significant role in magnetospheric dynamics, the conditions under which PLR activity occurs and its relative importance in precipitating energetic particles compared with that of other types of waves such as whistlers and plasmaspheric hiss [Lyons et al., 1972] are not known at present. A systematic survey of PLR activity is now under way to answer some of the questions, and the results will be reported at a later date. In this paper we present only the results of a detailed case study during a 13-day period that included a major magnetic storm and some isolated substorm activity.

The PLR phenomenon can take a wide variety of spectral forms. In its simplest form, several line emissions may appear at harmonics of the power frequency (but usually with slight upward frequency shifts as will be discussed later). These line emissions sometimes initiate free-running emissions, the frequency of which may vary over a few kilohertz. A more subtle type of PLR effect takes place through wave-wave interactions in the magnetosphere. The PLR waves, close to or below the threshold of detection on standard spectrograms, can strongly affect the behavior of other emissions by cutting them off, by suddenly increasing their intensity, or by changing their frequency. This type of PLR activity is sometimes difficult to identify as such and contributes to the problem of assessing the impact of man-made VLF waves in the magnetosphere. Examples of various types of PLR effects will be shown in the next section.

Observations and Interpretations

An overview. Figure 1 shows variations in VLF wave intensity during the period June 14-26, 1965, as observed at Eights, Antarctica (75°W, $L \approx 4$). The top panel shows hourly values of the auroral electrojet (AE) index. A storm main phase started near 1100 UT on June 15 and lasted through June 17. There then followed a long quiet period except for brief interruptions by isolated substorm activity on June 22 and June 25. The four lower panels show VLF wave amplitude data in four frequency bands as indicated. The quantities plotted are maximum wave amplitudes in each 3-hour interval scaled from continuous analog chart records. The amplitude detectors had a 0.1 s rise time in order to discriminate against impulsive sferics propagating in the earth-ionosphere wave guide. Further, in scaling the chart records, amplitude peaks of less than 30-s duration were ignored so that strong, isolated bursts due to whistlers and other transient events would not affect the results. We can see that the wave activity is closely correlated with geomagnetic activity, a well known fact. The wave amplitudes in all

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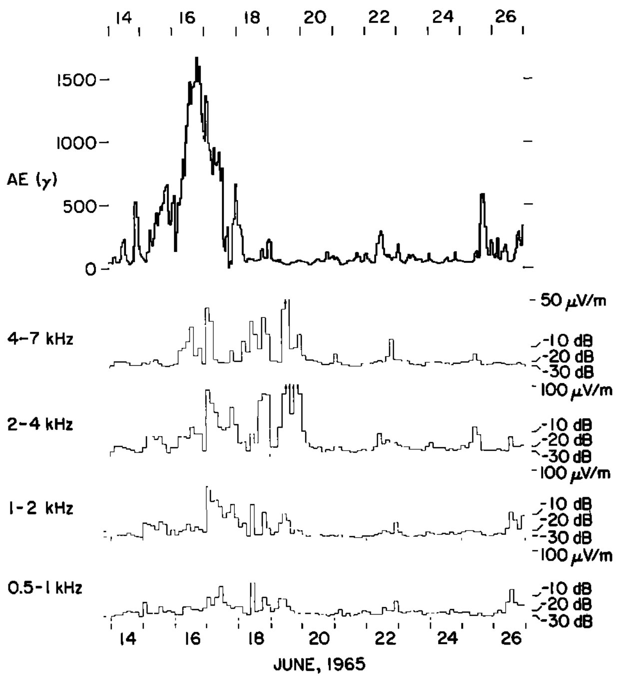

Fig. 1. VLF wave amplitude variations at Eights, Antarctica, during the period June 14-26, 1965. The top panel shows the auroral electrojet indices.

channels peak strongly during and following the magnetic storm, and even the small substorm activity on June 22 appears to be associated with enhanced wave activity.

In order to understand the nature of the wave activity represented in Figure 1 we shall examine broadband spectral data. Figures 2a and 2b show frequency-time spectrograms for the 13-day period in the 0- to 10- kHz range. The data shown are 1-min samples taken every 15 min (5, 20, 35, and 50 min after the hour). The series of dots running through the record are 5-kHz calibration marks at the beginning of each 1-min-long segment. In this presentation the gain of the spectrum analysis system was frequently adjusted so as to bring out spectral details of the most prominent features. Therefore the degree of darkness cannot be used as a measure of long-term variations in wave intensity. The blank areas are due to missing data.

Many different types of wave activity can be recognized in Figure 2. Dark vertical lines such as those that appear prominently on June 14 are due to whistlers. Sferics that are weaker but more numerous than whistlers form an almost continuous gray background in this display. Near 0000 UT on June 15 there is a hiss burst with a well-defined upper cutoff frequency that increases with time. Similar behavior is repeated at ~2200 UT on June 15 and again at ~0000 UT on June 18. This type of noise burst is commonly observed at mid-latitudes, but its origin has not been explained yet. It is possible that the noise is generated by clouds of energetic electrons that become dispersed as they drift around the earth. Particles having the highest energy would arrive first, and as progressively lower energy particles arrive at later times, they would generate waves at increasing frequencies. (We are assuming cyclotron resonance as the generation mechanism.) Although this explanation appears to be plausible, no solid experimental support for it has yet been found in particle data.

From ~2000 UT on June 15 to ~2000 UT on June 16, intense hiss appears above ~7 kHz. Near 0200 and 0300 UT on June 17 the hiss extends down to below 2 kHz and fluctuates rapidly in intensity. This type of hiss is generally confined to the auroral zone (commonly referred to as auroral hiss) but is occasionally observed at middle latitudes during magnetic storms [Helliwell, 1965; Morgan, 1977].

The June 16 and June 17 records show many discrete rising tone emissions or chorus between ~0700 and ~2100 UT.

On June 18 we see the first clear evidence of power line effects. Power-line-induced emissions appear as horizontal striations on these records (see, for example, the 4- to 7-kHz range in the 1205 UT run). A detailed examination of expanded spectrograms (examples will be shown later) shows that the PLR activity first appeared in the 0805 UT run on June 18 and continued until the 0020 UT run on June 19 except for a few brief interruptions. The striations are particularly noticeable around 1200 UT and from ~1700 to ~2000 UT. PLR reappears at 1005 UT on June 19 in the upper-frequency band and remains active until the end of the 0050 run on June 20. Near 0500 UT on June 19 there are slowly rising emissions, each lasting for about 1 min. Similar risers are seen again near 1300 UT on June 19 and near 1000 UT on June 25. These appear to be unrelated to PLR.

June 20 and 21 are exceptionally quiet days with little magnetospheric wave activity other than whistlers.

On June 22 there is an increase in wave activity, apparently in response to small substorm activity (see the AE index in Figure 1). From ~0900 to ~1100 UT and again from ~1500 to ~1700 UT there are rising tone emissions in the ~3- to 4- kHz range spaced ~30-50 s apart. It was confirmed by examining continuous recordings available for this period that these are quasi-periodic emissions [e.g., Helliwell, 1965; Ho, 1973]. PLR is seen again between the 1735 and 2005 runs in the ~5- to 7- kHz range.

June 23 and 24 show strong whistlers but little wave activity of any other kind.

On June 25, enhanced emission activity is observed between ~0800 and 1500 UT. An examination of expanded spectrograms shows detectable PLR from the 0820 run to the 1105 run. In most of these runs, PLR is mixed with banded hiss and is not the strongest type of emission. Later on, barely detectable PLR reappears in the 1450 run. In the intermediate runs, banded hiss dominates, and no clear PLR can be identified. It is not clear if and how the enhanced activity on June 25 is related to the substorm activity that started near 1430 UT.

Some horizontal striations in Figure 2 appear as though they could be due to PLR, but in fact they are not. Examples include the 0650 run on June 19 and the four consecutive runs starting at 0305 UT on June 21. Expanded spectrograms show these features to be quasi-constant frequency emissions triggered by whistlers. In some cases (i.e., between 1200 and 1400 UT, June 25), possible PLR is masked by banded hiss to make its identification difficult. For the purpose of this study any such questionable cases are not accepted as PLR events.

On the basis of the spectral information in Figure 2 we can determine what types of wave activity were associated with the amplitude peaks in Figure 1. On June 16 the peak in the 4- to 7- kHz channel was due to chorus. The sharp amplitude rise in the three channels covering 1-7 kHz at the beginning of June 17 was due to broadband auroral hiss. PLR activity was responsible for the peaks in the 2- to 4- and 4- to 7- kHz channels on June 18 and 19. On June 22 the 2- to 4- kHz peak can be associated with quasi-periodic emissions, and the 4- to 7- kHz peak with PLR. The peaks in 2- to 4- kHz and 4- to 7- kHz channels on June 25 are partly due to PLR. As was discussed earlier, PLR during this time was mixed with banded hiss.

It is significant that the largest-amplitude peaks in the storm recovery period were produced by PLR activity. We will now examine this activity in more detail.

PLR activity. Figure 3 shows two examples of PLR activity in much more detail in comparison with Figure 2. The top panel shows many line emissions strongly modulated in intensity at the two-hop whistler period. The bottom panel shows another example in which emissions starting at different frequencies merge to form continuous rising tone structures. Strong intensity modulation at the two-hop delay period is also evident here.

The PLR activity may show a great deal of variability in intensity as well as in spectral characteristics. For example, examine the record for the second half of June 18 in Figure 2. The PLR frequencies may change abruptly from one run to the next. The intensity may be greatly diminished as in the four consecutive runs starting at 1320 UT; it may fall below detectable limits for brief periods as it did during the 1750 and 2020 UT runs. The factors affecting the PLR are not well understood at present, but presumably they include propagation conditions, energetic particle parameters, and the presence of other wave activity that may either enhance or suppress the growth of PLR waves.

One important condition required for PLR activity appears to be good whistler mode echoing. A detailed examination of the PLR activity on June 18, 19, and 22 indicates a strong tendency for it to occur when whistlers show long-enduring echoes. On the basis of this and previous case studies [Helliwell et al., 1975; Park and Helliwell, 1977] it appears safe to state that when PLR is observed, strong whistler echo trains can also be expected. This is not difficult to understand, since PLR entering the magnetosphere is likely to be very weak and therefore requires repeated passages through the wave growth region before it gains sufficient amplitude to produce any detectable effects. However, there are of course periods of strong whistler echoes with no clear sign of PLR activity.

The frequency of PLR observed during the period of this study ranged from ~2.5 to ~9 kHz. It is characteristic of stimulated line emissions (whether by power lines or transmitters) to exhibit frequency broadening on the upper side of the stimulating frequency [Stiles and Helliwell, 1975; Helliwell et al., 1975]. When several adjacent lines of PLR are activated simultaneously (as is usually the case), they often appear as a diffuse band of noise that is difficult to distinguish from hiss unless adequate frequency resolution is used in spectrum analysis and display (see Figure 5). The spectrum analysis system used in this study provided 10-Hz frequency resolution for an analyzed bandwidth of 5 kHz or less and 20-Hz resolution for a bandwidth of 5-10 kHz.

In Figure 4 the top panel shows two distinct noise bands covering ~0.7-2.2 and ~3.2-5.5 kHz. These two bands are reproduced below in expanded frequency scales. The middle panel shows the upper-frequency band with discrete line emissions; they are well separated from one another below ~4 kHz but become less distinguishable at higher frequencies. The lower-frequency band in the bottom panel shows an unusual bicycle chain-like spectral shape, but there is no hint of any line structure. The origin of this exotic emission is not known.

Figure 5 shows another example from 15 min later in a similar format. The middle panel clearly shows strong line emissions that are difficult to recognize in the 0- to 10- kHz spectrogram above. Two whistler echo trains starting at approximately 20 and 30 s appear to weaken the line emissions until they become unrecognizable near 35 s. Rising tone emissions above ~5.5 kHz are similarly affected. Thus we infer that both types of emissions shared their magnetospheric path(s) with the whistlers. On the other hand, the 'bicycle chain' in the lower-frequency band remains unaffected by the whistlers; furthermore, its period is considerably longer than the two-hop whistler delay. This suggests that the bicycle chain noise was generated on a different path.

Figure 6 illustrates another type of PLR activity that occurred on June 22. In the upper panel, two lines spaced 120 Hz apart run across the record near 5 kHz. They appear to stimulate many rising tone emissions and also mark the upper-frequency cutoff of diffuse hiss. In the lower panel, which was taken about 15 min later, the horizontal lines are no longer visible, and the hiss cutoff frequency has moved slightly upward. Although no line emissions are visible, several characteristic frequencies can be identified near the top of the hiss band where many emissions originate. We can also see that many whistlers are abruptly cut off at the same characteristic frequencies. These frequencies are difficult to measure accurately, but they are spaced 120 Hz apart within about ±10 Hz. We suggest that the emission triggering and whistler cutoff are controlled by power line harmonics that are too weak to be detectable on this record. In support of this interpretation we cite the results of controlled wave injection experiments at Siple, Antarctica, in which weak injected signals, barely detectable on spectral records, produced strong wave-wave interaction effects similar to those illustrated here [Helliwell and Katsufrakis, 1974]. This type of PLR effect is difficult to identify as such, and in

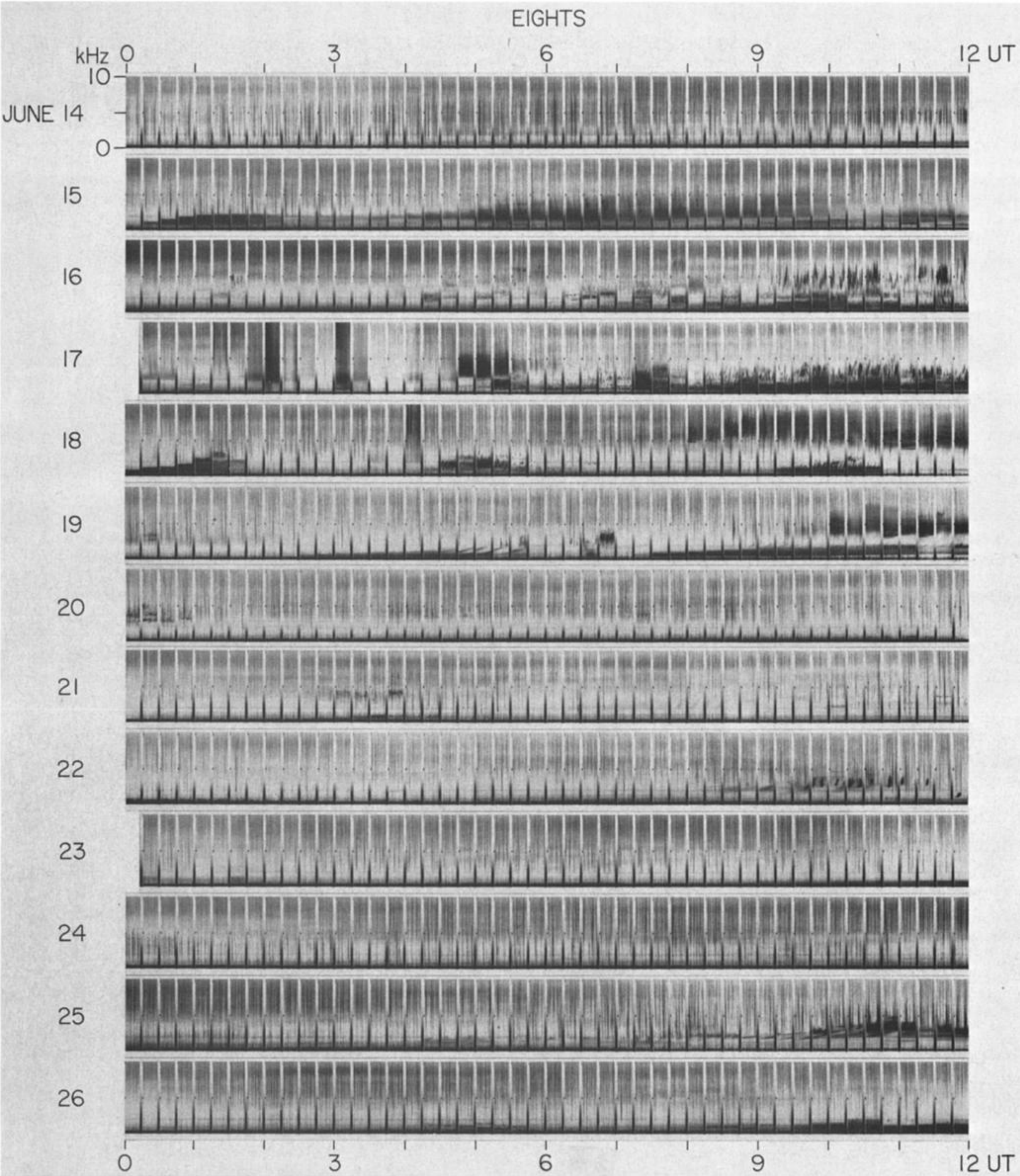

Fig. 2a. VLF spectra observed at Eights, Antarctica, for 0000-1200 UT, June 14-26, 1965. Recordings were made for 1 min every 15 min starting at 5, 20, 35, and 50 min past each hour. 5-kHz calibration marks can be seen at the beginning of each 1-min segment. Blank areas are due to missing data.

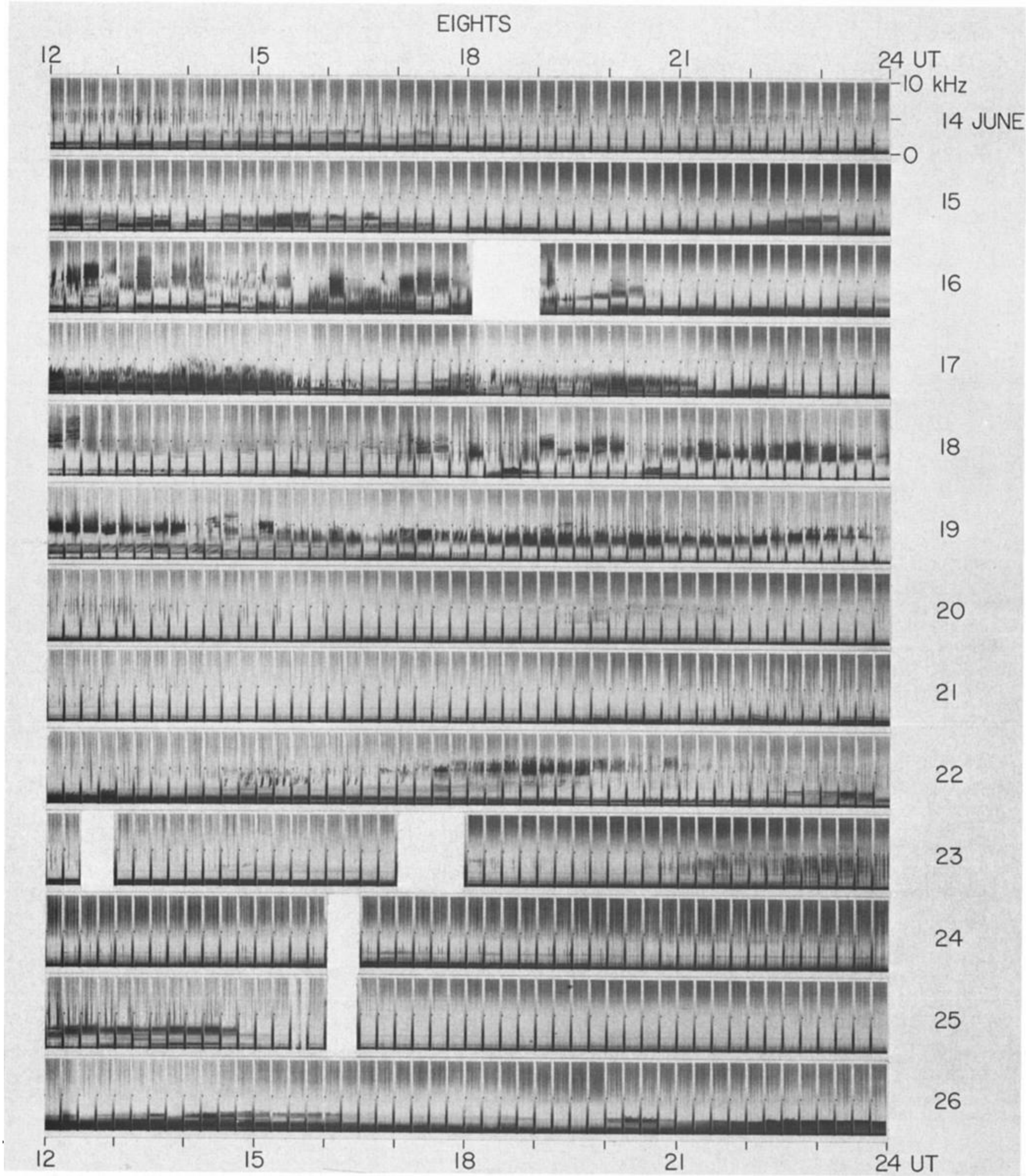

Fig. 2b. VLF spectra observed at Eights, Antarctica, for 1200-2400 UT, June 14-26, 1965. Recordings were made for 1 min every 15 min starting at 5, 20, 35, and 50 min past each hour. 5-kHz calibration marks can be seen at the beginning of each 1-min segment. Blank areas are due to missing data.

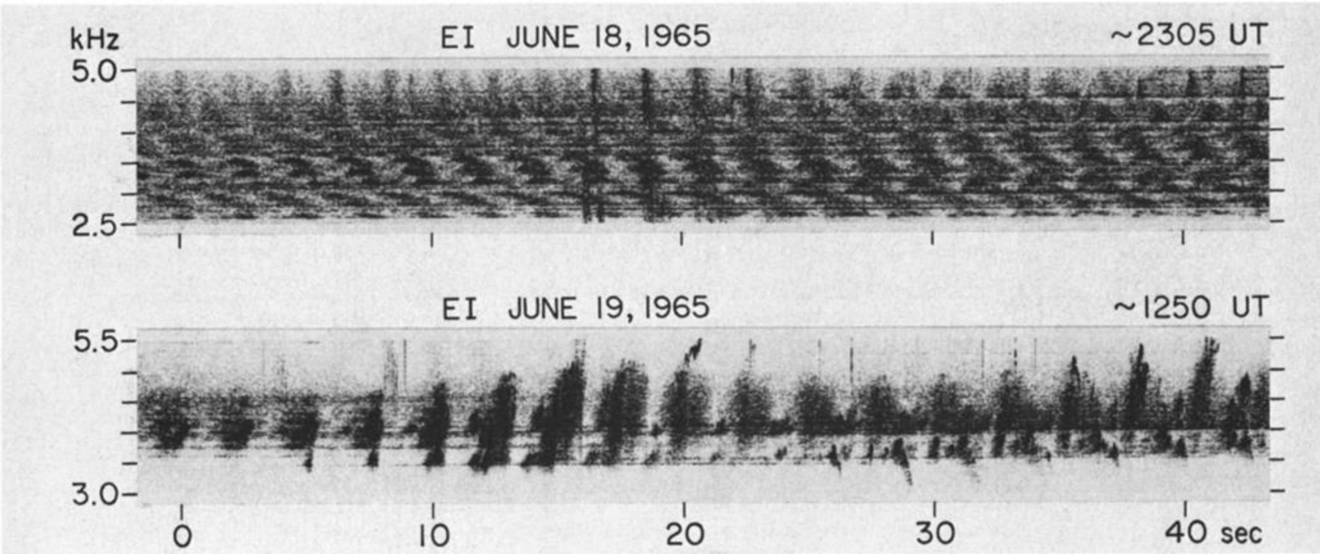

Fig. 3. Two examples of strong power line radiation recorded at Eights, Antarctica.

many cases the need to adopt conservative criteria could cause us to underestimate the importance of PLR.

The line emissions in the middle panel of Figure 5 are 120 Hz apart within the experimental error of ~±5 Hz. In many cases, however, the frequency separations between adjacent lines are not exact multiples of 60 Hz, the minimum separation reaching as low as 35 Hz. Figures 3 and 4 both show examples of this. Such effects were also noted by Helliwell et al [1975]. One simple explanation is that there may be two (or more) uncoupled power systems operating at slightly different frequencies. At 4 kHz a 35-Hz separation could be explained if the fundamental frequency of one power system deviated from 60 Hz by 0.6%. Park and Helliwell [1977] reported a case in which spectral records from Roberval, Quebec, in fact showed evidence of two uncoupled power systems operating at slightly different frequencies, thus causing difficulties in associating magnetospheric line frequencies with local power line harmonic frequencies. Unfortunately, it was not possible in the present

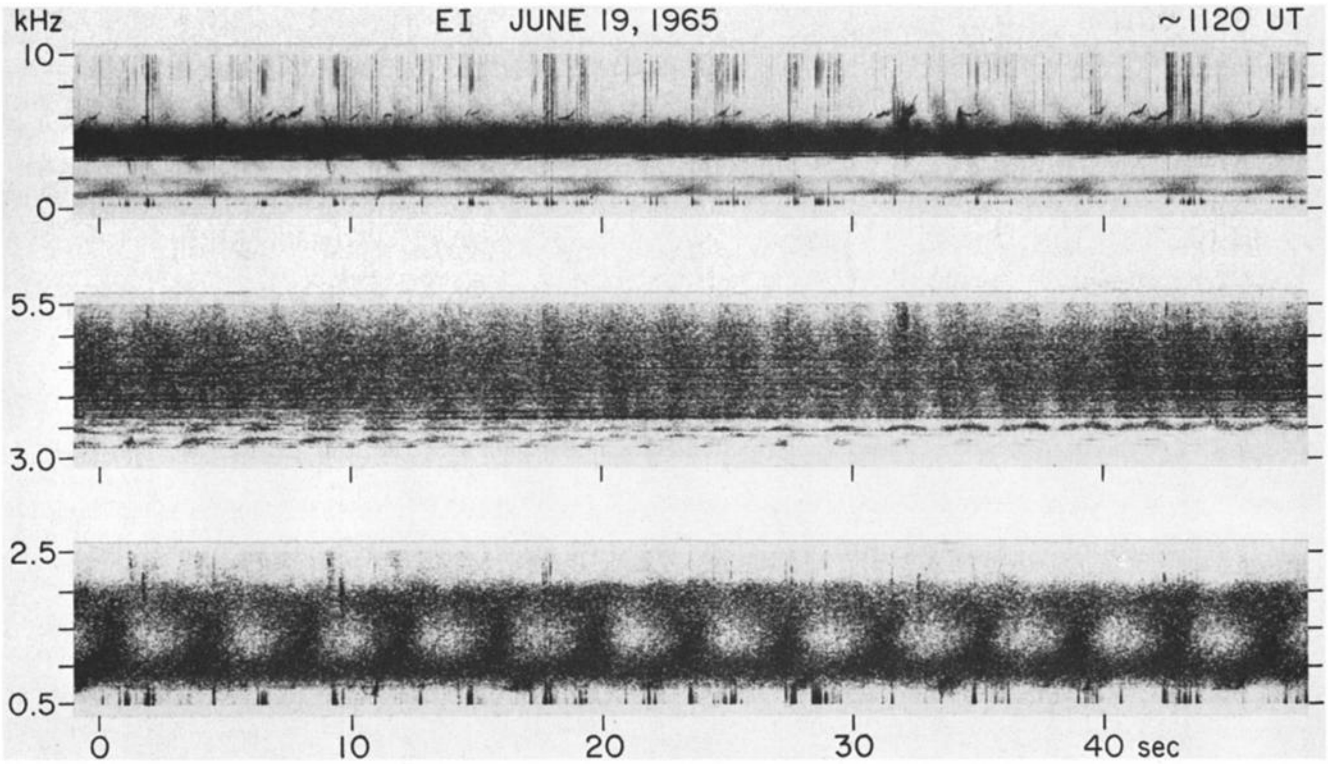

Fig. 4. (Top) Two distinct emission bands observed at Eights, Antarctica. (Middle and bottom) The two bands in expanded frequency scale.

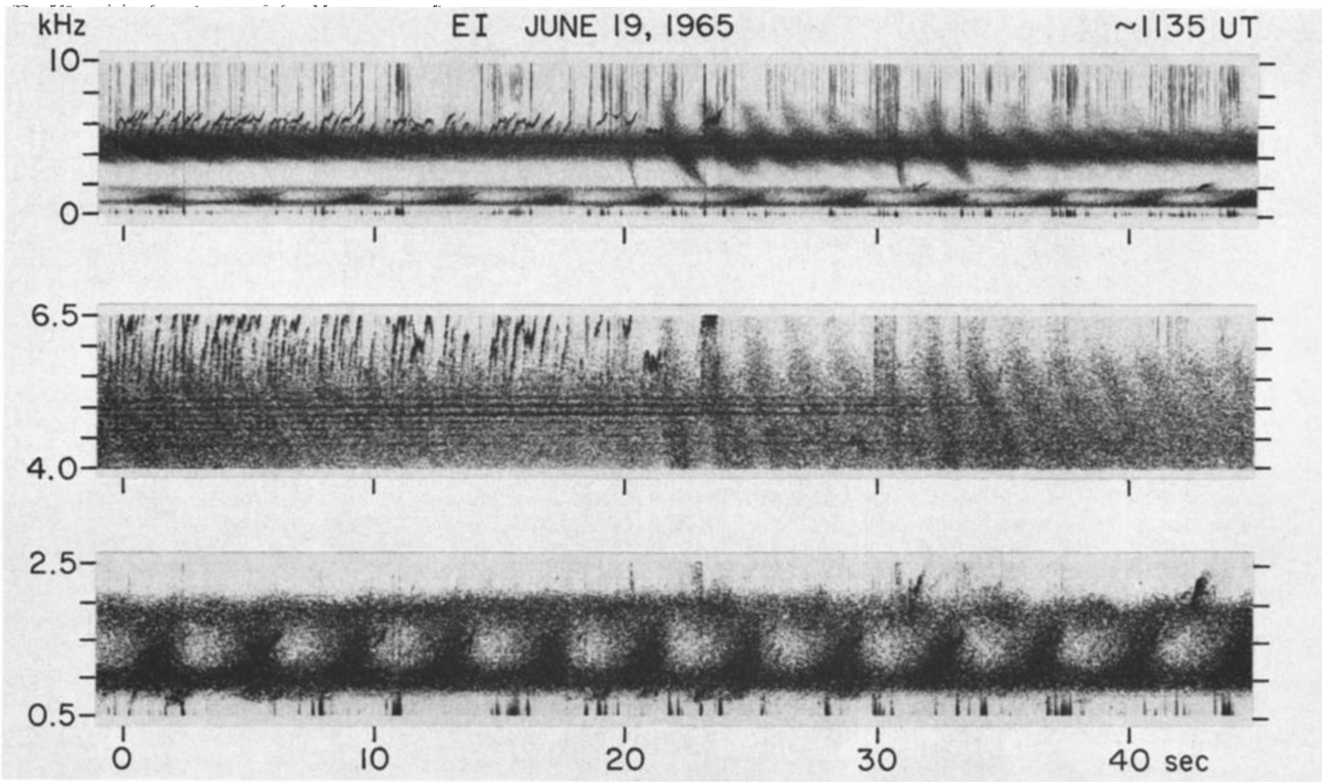

Fig. 5. Same as Figure 4, 15 min later.

case to check local power line frequencies to test the above explanation.

During the period of this study, VLF recordings were also made at Byrd and Argentine Islands, Antarctica, as well as at three North American stations: Norwich, Vermont; Great Whale River, Quebec; and Suffield, Alberta. PLR activity was noted at all of these stations. Frequently, the same emissions were observed at several stations, as illustrated in Figure 7. Most of the power-line-induced emissions can be seen at all stations except Suffield, where there is only a hint that the horizontal line near 5 kHz may be PLR that also appears on other stations' records. Eights and Norwich records clearly show the emissions echoing from hemisphere to hemisphere. The series of dots near 7 kHz at Argentine Islands and near 8 kHz at Norwich are time marks generated at the recording stations.

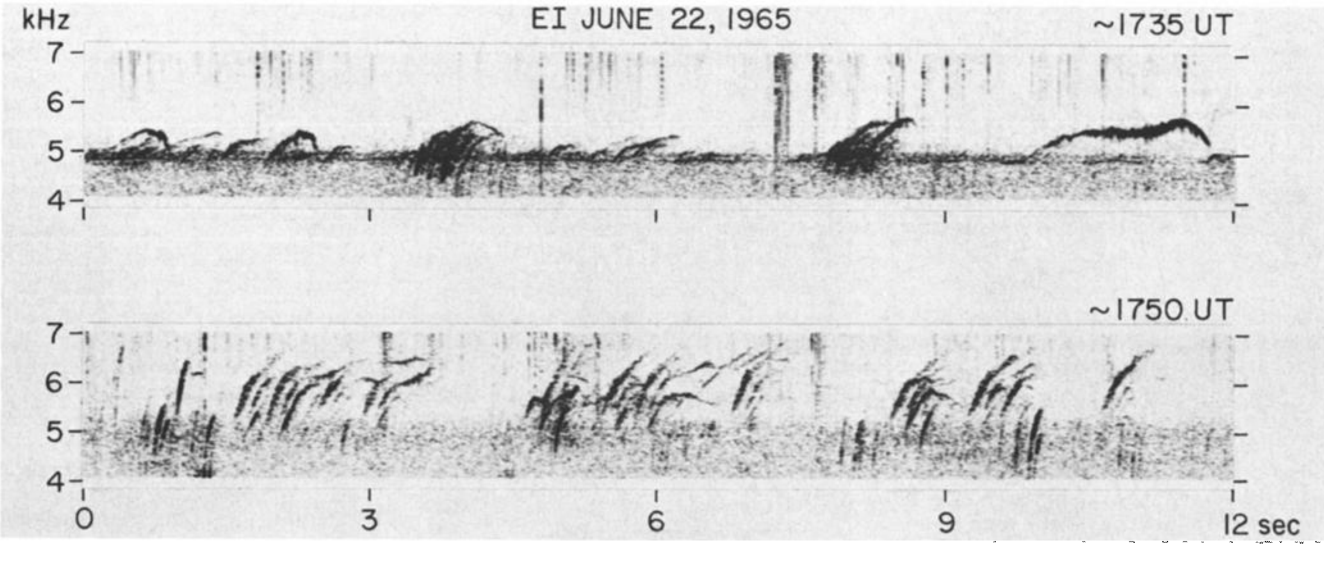

Fig. 6. Two spectrograms taken 15 min apart at Eights, Antarctica. The lower panel suggests strong power line control of whistlers and emissions, although power line harmonics themselves are not detectable. Whistler traces above the nose frequency extend up to ~5.5 kHz. See text for details.

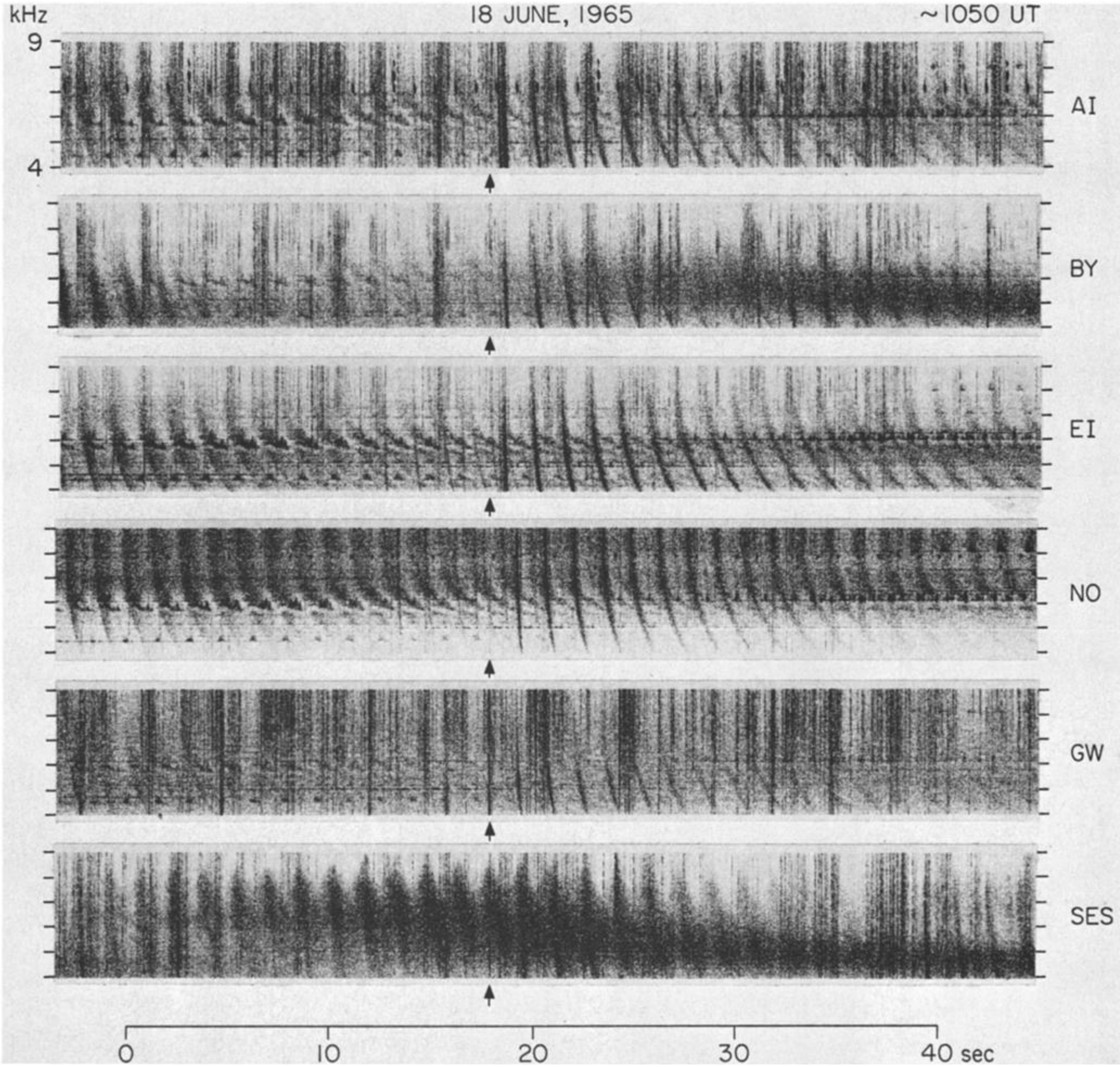

Fig. 7. Simultaneous recordings from Argentine Islands (AI), Byrd (BY), and Eights (EI), Antarctica Norwich (NO), Vermont; Great Whale River (GW), Quebec; and Suffield (SES), Alberta. The arrows mark the causative sferic that produced the long whistler echo train observed at all the stations. The AI and NO records show 1-s time marks near 7 and 8 kHz, respectively.

The arrows in Figure 7 mark the causative sferic in the northern hemisphere that excited the long whistler echo train. An examination of the southern hemisphere data on an expanded time scale shows six discrete one-hop whistler traces; however, the two-hop echoes at Norwich and Great Whale River as well as all subsequent echoes in both hemispheres show only one component. This means that of the six ducts that were capable of guiding one-hop whistlers, only one produced echoes. This echo-producing duct will be referred to as duct A. The whistlers at Suffield are more diffuse than those received at other stations, and their echo period indicates that they were propagating on a path other than duct A.

The top of Figure 8 shows the one-hop Eights whistler of Figure 7 in expanded time scale. Duct A is marked on the spectrogram and is retraced in the sketch below. The dots in the sketch show one-hop travel times of power-line-induced emissions at six different frequencies, and the good agreement with the whistler dispersion indicates that all the emissions were generated in duct A. This is true for all the line emissions in Figure 7 that show clear echoing. Thus we conclude that all the PLR activity in Figure 7 originated in one duct and spread to the various receiving stations in the earth-ionosphere wave guide. This finding is consistent with the previously noted observation that PLR activity seems to occur when conditions are suitable for whistler echoing. Figure 9 shows the L value and local time of the stations when the recordings in Figure 7 were made (1050 UT).

Discussion and Conclusions

During the storm recovery period the most intense magnetospheric waves observed at Eights, Antarctica, have been identified as PLR and associated emissions. Their propagation paths varied from L = 3.4 to 4.4, and the frequency range was ~3-9 kHz. Using electron densities deduced from simultaneous whistler data, one determines that the electrons that are cyclotron-resonating with the observed PLR waves at the equator would require parallel energies of ~3.5-26 keV. As these waves propagate down along geomagnetic field lines, they resonate with increasingly energetic particles. Thus PLR waves can cause pitch angle scattering of electrons in wide energy ranges extending from ~10^3 to ~10^6 eV. This may be an important factor in the decay of energetic electrons injected during magnetic storms. (See Helliwell et al. [1975] for a discussion of particle diffusion time into the loss cone in the presence of PLR.)

It is important to note that only ducted waves can be observed on the ground. The strong PLR waves discussed here were confined to a few selected ducts that occupy only a small fraction (perhaps less than 1%) of the magnetospheric volume. However, it is possible that PLR propagating in the unducted mode behaves in a manner similar to the ducted component. This has yet to be clearly demonstrated, although there has been some statistical evidence suggesting that chorus observed by the Ogo 3 satellite in the high-altitude magnetosphere was triggered by unducted PLR [Luette et al., 1977]. After PLR waves grow and trigger emissions inside a duct, a part of the resulting wave energy may leak out of the duct and fall into the unducted regime. The waves that leak out of the duct at high altitudes would not be observed on the ground but could have important effects on energetic electrons. It is important to learn how the wave energy is divided between ducted and unducted modes. This would require a wave detector on a satellite with a nearly field-aligned orbit or a means of mapping wave-induced particle precipitation patterns in the ionosphere.

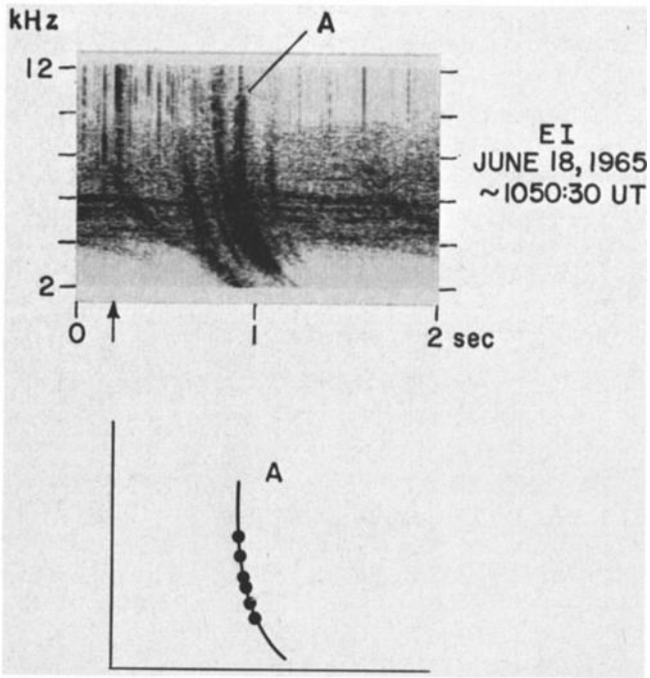

Fig. 8. An expanded spectrogram of the one-hop whistler of Figure 7 observed at Eights. The whistler component marked A in the spectrogram is retraced below. The dots indicate one-hop delay times of echoing power line harmonics of Figure 7.

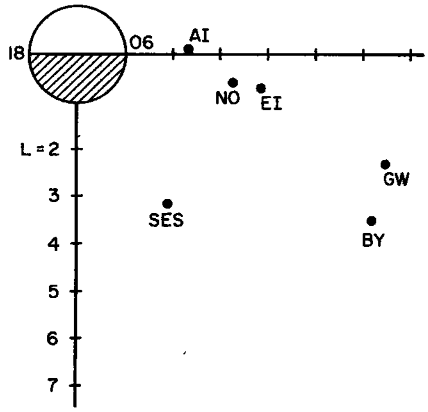

Fig. 9. Local time (solar) and L value of the VLF stations in Figure 7.

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