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FAST FLUCTUATIONS IN THE ARRIVAL BEARING OF MAGNETOSPHERICALLY PROPAGATING SIGNALS FROM THE SIPLE, ANTARCTICA, VLF TRANSMITTER

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Abstract. Signals propagating from the Siple, Antarctica, VLF transmitter to the conjugate station at Roberval, Quebec, Canada (L ~ 4.2), are generally multipath in nature. From previously reported initial observations at Roberval with a tracking receiver/direction finder (TR/DF) it was found that the directional properties of the received signals were stable for only minutes at a time, compared to the tens of minutes that had been expected from earlier dispersion analyses of whistlers. This effect was further investigated in the present study of TR/DF observations of multipath Siple signals in 1977. In a case study from May 20, 1977, the TR/DF consistently obtained directional information on the arrival bearings of multipath signals whose amplitude at the receiver was ~5 dB or more above that of other signals within the 340-Hz passband of the frequency-tracking filter. It was found that the arrival bearing of the strongest signal shifted widely within minutes. The sequence of shifts over a 1-hour period, coupled with the occasional appearance of power line radiation activity, may possibly be induced by the eastward gradient drift of low-energy (≃1-2 keV) 'clouds' of electrons through a pattern of whistler ducts. This interpretation was suggested by the rapidity (~10-100 s) with which signal amplitudes rose and fell by greater than ~10 dB on individual paths. The sudden turn-ons and turn-offs are tentatively attributed to the 'threshold' effect being reported elsewhere, in which temporal growth of Siple transmitter signals suddenly occurs as the amplitude of the injected waves reaches a particular level. In the present case the phenomenon is believed to occur at constant wave level as the result of changes in particle flux associated with drifting structure in the low-energy electrons. Other effects observed in the primary case study were a slow northward movement on a time scale of about 30 min of the bearing of the stronger signals. This movement is believed to be associated with quiet-day convection. Also observed were small-scale ($\Delta\theta$ ~ 10°-20°) fluctuations on a time scale of several minutes in the arrival bearing of signals from a particular path. These fluctuations may be due to a temporal modulation of propagation conditions between the 'ends' of magnetospheric ducts and the lower boundary of the ionosphere.

1. Introduction

In the last two decades, substantial progress has been made on magnetospheric very low frequency wave diagnostics using frequency-time or dispersion techniques. However, important features of the propagation circuit remain poorly known, among them the properties and dynamics of ducts, the manner of duct excitation, and propagation between duct 'endpoints' and the lower boundary of the ionosphere [e.g., Walker, 1976]. These questions are further complicated by the fact that interhemispheric propagation usually occurs on multiple magnetospheric paths or ducts, in the case of both natural whistlers and man-made signals.

VLF transmitters [e.g., Helliwell and Katsufrakis, 1974] and direction-finding receivers [e.g., Leavitt et al., 1978] represent two important new means of investigating the hemisphere-to-hemisphere propagation circuits. The transmitter provides a means of exciting magnetospheric paths from a known location and at controlled power levels, while the direction finder provides previously unavailable information on the ionospheric exit points of whistler paths. This note describes how the Stanford tracking receiver/direction finder (TR/DF) system responds to multipath signals from the Siple, Antarctica, VLF transmitter, and presents some first results on fast fluctuations or 'scintillations' of signal path endpoints during relatively calm magnetic conditions.

By isolating their frequency-time traces on spectrograms, individual whistler components have been observed to last from minutes to hours. However, a systematic study of this subject has not yet been performed, partly owing to lack of information on whistler source location and also to the great complexity of many whistler forms. The duration of identifiable whistler components appears to be a function of latitude; prominent components near L = 2 may show little change over several hours, while those propagating at L ~ 4 frequently are identifiable for less than 1 hour.

The TR/DF system and a University of Tokyo DF system [Tsuruda and Hayashi, 1975] were initially deployed at Roberval, Quebec, Canada, conjugate to Siple, in a test campaign in 1975. At that time it was expected from experience with conventional whistler records that the indicated arrival bearings of Siple transmitter signals would remain relatively stable for periods ranging from a few minutes to 1 hour. There were indeed many intervals of well-behaved bearings [Leavitt et al., 1978], but they tended to be relatively brief, of 2 to 10 min duration. One explanation for certain periods of unreliable data, pointed out by Tsuruda and Ikeda [1979], is the reception of multipath signals of comparable intensity. Another factor affecting the duration of stable periods is the dependence of Siple signal reception on temporal wave growth along the magnetospheric path. This dependence, apparently manifested by changes in the conditions for growth along a number of magnetospheric paths and by corresponding changes in arrival bearing data, is discussed in the present paper.

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The VLF data reported here were recorded under an International Magnetosphere Study program of support for VLF direction finding. The recordings were made at Roberval on May 20 and July 26, 1977, during reception of strong whistler mode signals from the Siple transmitter. Magnetic conditions were relatively calm (Kp ~ 2 on May 20; Kp ~ 1 on July 27); the overall circumstances were typical of strong Siple signal receptions as summarized by Carpenter and Miller [1976].

The operation of the Siple I Zeus VLF transmitter has been described by Helliwell and Katsufrakis [1974, 1978]. A description of the TR/DF system and initial results from its application have been presented by Leavitt [1975] and by Leavitt et al. [1978]. Briefly, inputs from crossed loops and a vertical antenna are processed through a frequency-traking loop which follows quasi-coherent signals with a filter of 340-Hz bandwidth. The tracked outputs from the antennas are then processed by direction-finding circuitry that calculates the apparent azimuth of arrival of the signal. The calculation assumes that the major axis of the polarization ellipse of the wave electric field is in the plane of incidence of the wave. Departures from this assumption lead to polarization error [Leavitt, 1975]. The evidence obtained thus far suggests that, as had been predicted, polarization error is frequency-dependent. This condition can often be detected in the data [Leavitt et al., 1978]. In the present study the variations in bearing of individual quasi-coherent signals with frequency were relatively small, and thus polarization error is not believed to be a major factor in the reported results.

Section 2 discusses the interpretation of bearings obtained under multipath conditions. Section 3 presents some results of tracking of multipath Siple transmitter signals.

2. Acquisition of Signal-Bearing Information Under Multipath Conditions

Under multipath conditions on Siple transmitter signals the TR/DF has been found to provide

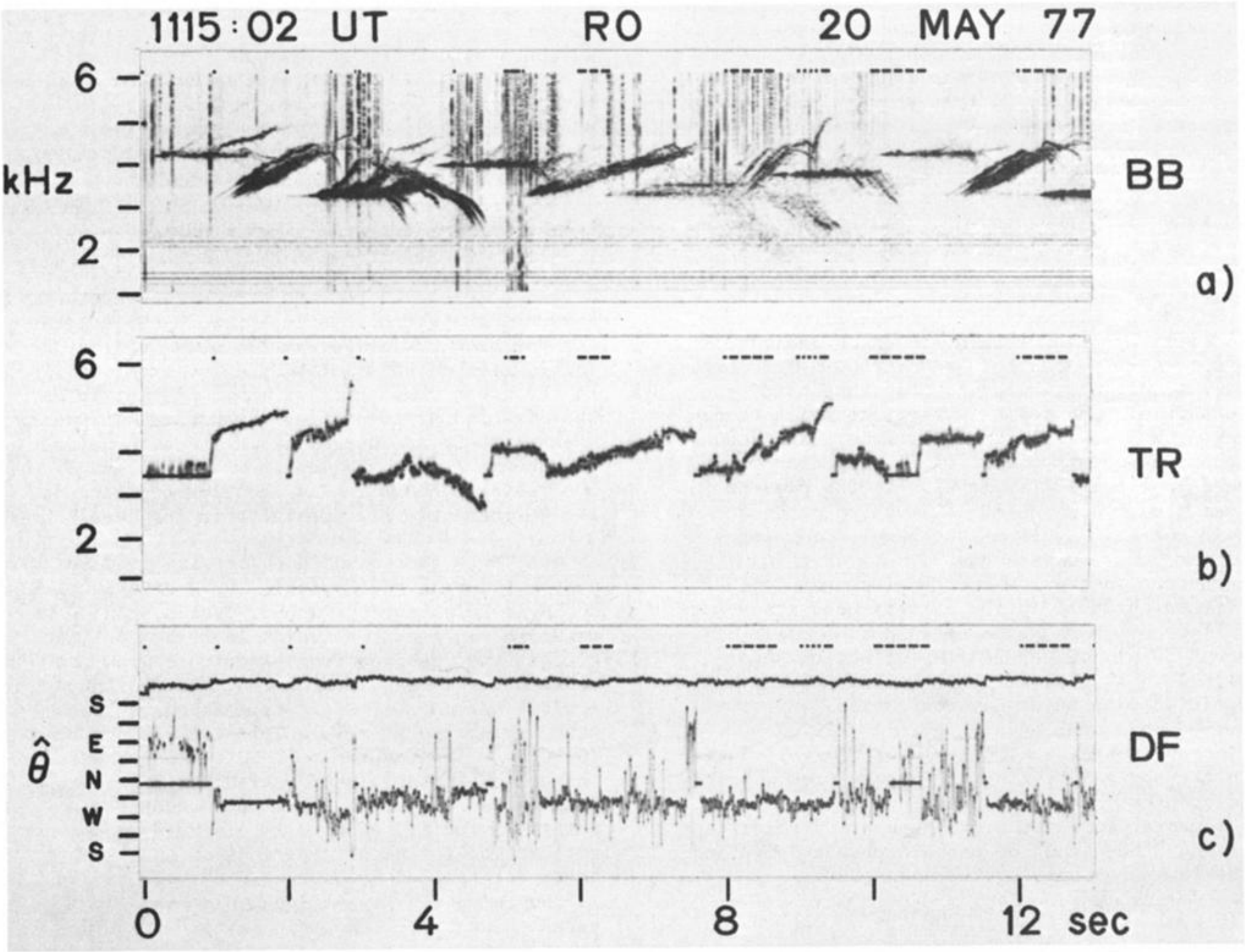

Fig. 1. Spectrograms illustrating application of the tracker/direction-finding receiver to multipath signals propagating to Roberval, Quebec, from the Siple, Antarctica, VLF transmitter. (a) Broadband spectrum transmitted from Siple as a sequence of 1-s pulses and frequency ramps. (b) Replica of the center frequency of the 340-Hz tracking filter. (c) Apparent direction of arrival of the tracked signal in magnetic coordinates. The upper trace is a highly compressed indication of log signal strength within the tracker passband.

useful information both when a single quasi-coherent signal is present in its 340-Hz passband and when one of several signals within the passband exceeds all others in amplitude by 5-10 dB [Leavitt et al., 1978]. The observation of a single signal frequently occurs because of a tendency for emissions triggered by the transmitter to vary in frequency with time and thus to become isolated in frequency-time space. Isolation of signals is also achieved by transmission of frequency ramps, which may separate into resolvable elements when the group delays on the multiple paths are sufficiently different.

Figure 1 shows a period of tracking/direction finding on a sequence of alternating 1-s pulses, and rising and falling frequency ramps. Figures 1a, 1b, and 1c show a Roberval spectrogram of broadband wave activity (1-6 kHz), a replica of the tracker center frequency, and the apparent arrival bearing $\hat{\theta}$, referred to local magnetic north, respectively. The multipath nature of the propagation is illustrated near t = 8-9 s, when several rising ramp segments show a spread of ~0.4 s in arrival time (a single ramp was transmitted).

Tracking of a triggered emission, isolated in frequency-time space, is illustrated from t = 1 to 2 s (see lower time scale). The tracking and bearing fluctuations (Figures 1b and 1c) are relatively small at this time. Following t = 2 s the tracker path is mostly along frequency ramps, pulses, and triggered emissions; the tracking and DF traces show increased fluctuations, apparently due to the effects of multiple signals within the tracker passband. However, there is a well-defined average bearing to the west of north. The smallness of the scatter (~±20°-30°) is attributed to two factors: an actual clustering of individual path bearings and the greater amplitude of one of the multipath signals.

The clustering of the individual bearings is inferred from the fact that the tracker, with its 340-Hz filter, samples only part of the faster frequency ramps at a time and thus is capable of giving information on the stronger and the more isolated of the ramp components. In Figure 1, the ramp at t ~ 12 s is at times spread over ~400 Hz, while the one at t = 8-9 s covers ~800 Hz. No large scatter in bearing was indicated as the tracker 'wandered' through these signals and others of the immediate period

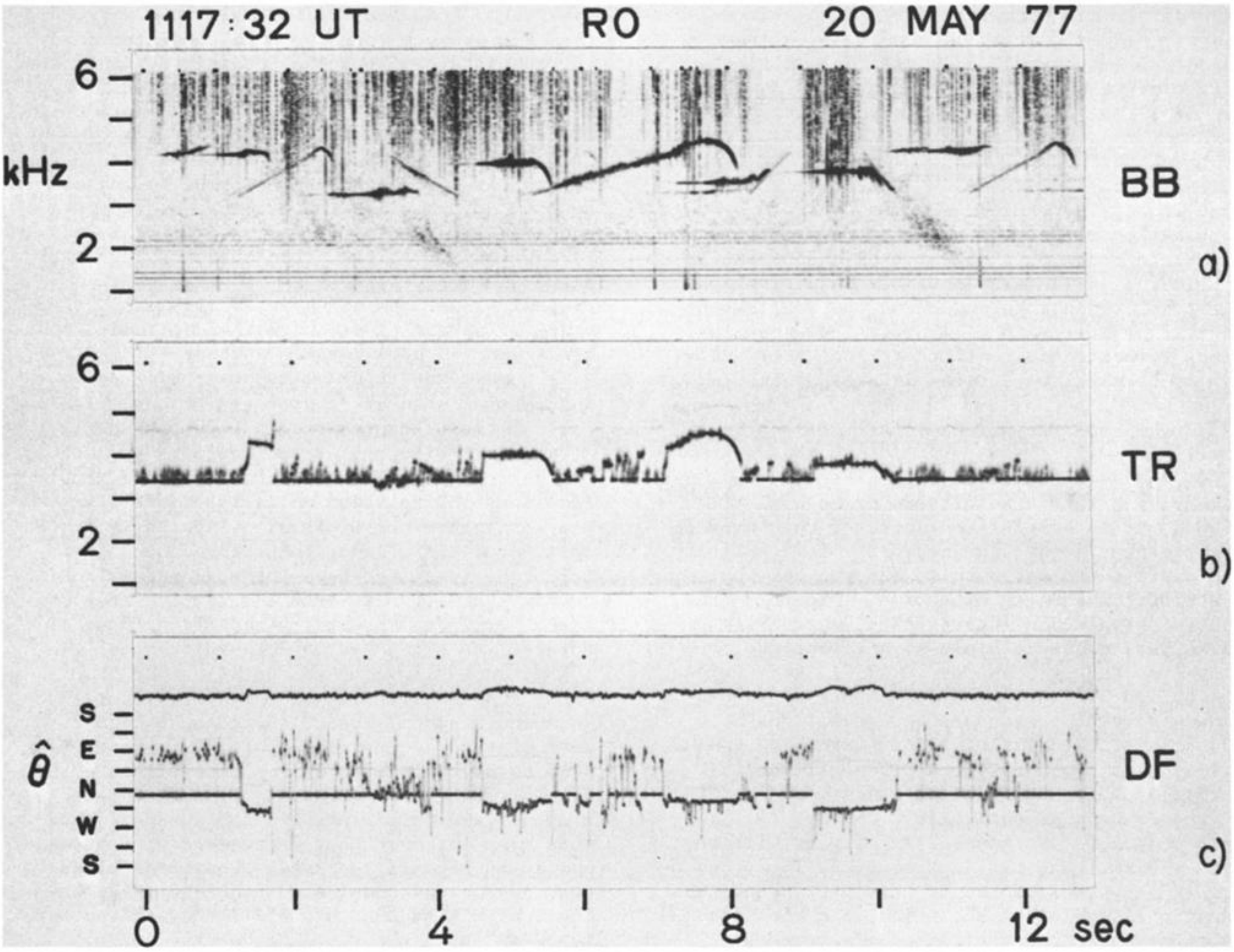

Fig. 2. Similar to Figure 1, but recorded ~2 min later, when power delivered to the Siple antenna had been reduced by 12 dB. The amount of visually detectable multipath activity on the broadband record is sharply reduced in comparison to Figure 1, and there are corresponding improvements in the tracking and bearing statistics.

(see below for data on bearings that were widely separated).

The presence of a signal of greater amplitude was indicated by progressively attenuating the signals at the input to a spectrum analyzer. The filmed record revealed one of the multipath elements to be ~5 dB stronger than any other. This finding was supported by a power-stepping experiment run in 5-min cycles on the same day (May 20) from 1110 to 1155 UT. The record of Figure 1 represented a maximum power of 24 kW to the Siple antenna. In five subsequent intervals separated by ~50 s the power was decreased in steps of 4 dB. At the -12-dB step the received spectrum (Figure 2a) appeared to involve single-path propagation. The travel time of the elements was found to coincide with that of the strongest element identified in the amplitude analysis. Figures 2b and 2c show the DF analysis for this case. There was a good deal of spurious triggering of the tracker (due to overly sensitive setting of the tracking controls), but four episodes of tracking on Siple signals are clearly identified. The bearings indicated agree within ~10° with the average bearing of Figure 1, recorded ~2 min earlier.

In Figure 2c there is a more or less discrete ~10° difference between the bearings at t = 7-8 and t = 9-10 s. This difference is not understood. It may be due to a residual multipath effect or to statistical fluctuations in the manner in which wave energy was concentrated within the duct and along the ionospheric segments of the path.

It is concluded from the foregoing that under some multipath conditions it is possible by a combination of methods to obtain useful directional information on signals of exceptional amplitude. It is also possible on a sampling basis to obtain information on the bearings of individual multipath elements. These conclusions form the basis of the following DF analysis of temporal variations in arrival bearings.

3. Temporal Variations in Arrival Bearings

In the analysis of wave-particle interactions involving either transmitters or natural VLF signals it is helpful to know over what type of magnetospheric path structure the wave activity was distributed and also to observe how that distribution changed with time. Figure 3 provides a simplified interpretive diagram of temporal variations in Siple signal bearings observed at Roberval on May 20, 1977, and during the period ~1105-1150 UT (~0630 MLT). Dashed lines indicate the ionospheric positions at 100-km altitude of field lines extending to 4.1 and 4.6 R_E in a hybrid Olson-Pfitzer/international geomagnetic reference field model of the earth's magnetic field [Seely, 1977]. Duct endpoints are modeled as circles with radius ~10 km. The bearings of ducts 1, 2, and 3 are roughly those found in the TR/DF data. The additional endpoints shown indicate the presence of other paths and their approximate bearings but do not reproduce actual details of any measured fine structure.

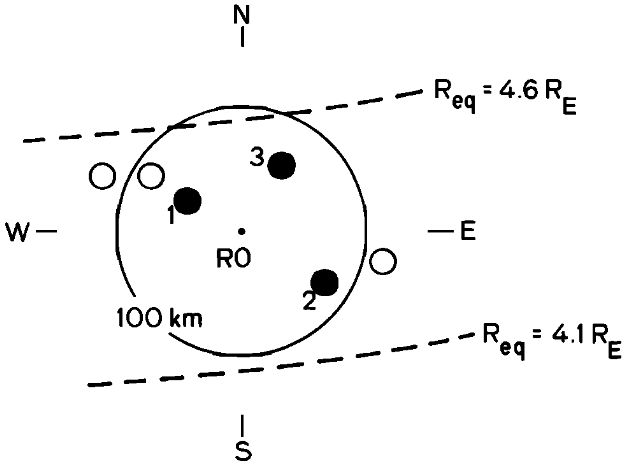

Fig. 3. Interpretive model of signal path endpoint activity observed from Roberval, Quebec, on May 20, 1977. Geographic coordinates are indicated. See the text for further details.

The model of duct endpoints as circles of radius 10 km is broadly consistent with data, although not intended to be definitive about the actual dimensions of ducts in space. Angerami [1970] found from an Ogo 3 spacecraft case study that the latitudinal extent of ducts near L = 4.5 was roughly 20 km when mapped to the ionosphere. From the indirect evidence he inferred that the longitudinal extent of the ducts was ~4-8 times greater, but no more than 4° overall. In previous tracker/DF measurements it was found that Siple and whistler path endpoints can frequently be localized to regions less than 50 km in both east-west and north-south extent [Seely, 1977; Leavitt et al., 1978]. Thus from the perspective of the TR/DF the wave energy appears to be relatively concentrated. This does not necessarily imply an absence of spreading of ducts in longitude of the kind reported by Angerami, however.

Although the TR/DF does not provide range information when it is operated at a single location, the distances from Roberval to paths 1, 2, and 3 in Figure 3 are believed to be accurate within ± ~ 30 km, based on the following considerations. Dispersion analysis of whistlers propagating on the Siple signal paths indicated that the field-aligned paths terminated in a belt roughly centered on Roberval and extending no more than 100 km north and south of the station. Previous dispersion and DF analyses of Roberval data [Seely, 1977; Leavitt et al., 1978], including comparisons of output from a TR/DF and a University of Tokyo DF system [Tsuruda and Hayashi, 1975], showed that signals with features comparable to those reported here tend to have observed exit points within a radius of 50-120 km. Paths 1, 2, and 3 of the present case were placed in the lower part of this range because they represented the stronger multipath signals received. Positions closer than 50 km were considered to be unlikely because of the reduced probability of duct occurrence at short range. (When nearly overhead signals do occur, there is an increased probability of polarization error [Leavitt et al., 1978], an effect that was not detected during the May 20 case study.) Positions beyond about 150 km were considered unlikely because of the

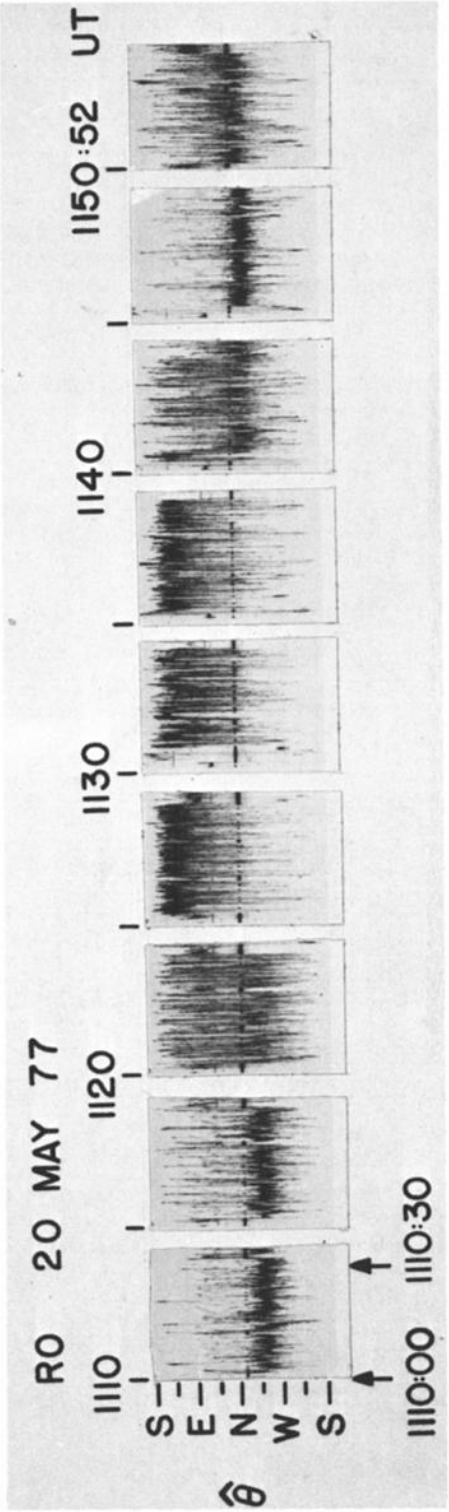

Fig. 4. Compressed spectrographic records showing relatively large temporal shifts in arrival bearing of Siple transmitter and other signals. The records represent 30-s segments taken at intervals of 5 min over a 40-min period on May 20, 1977. See the text for further details.

falloff in injected signal level with distance from the transmitter [Seely, 1977].

The following effects were observed on May 20, 1977: (1) rapid shifts, within minutes, from one path to another of the bearing of the strongest signal; (2) slow northward movement, on a time scale of ~30 min, of the bearing of the stronger signals; and (3) small-scale ($\Delta\theta \sim 10°-20°$) fluctuations in the arrival bearing of signals from a particular path on a time scale of several minutes.

Fast switching between paths is illustrated in Figure 4 by means of compressed, 30-s-long records of arrival bearing taken once each 5 min from 1110 to 1150 UT (the final record is at 1150:52 because of an interruption for calibration). These records are similar to those of Figure 1c, showing essentially continuous bearing information on signals produced at the highest step of the 5-min power-stepping sequence. At 1110 and 1115 there was a well-defined average bearing in the northwest (see also Figure 1c for 1115), and it is inferred that most of the multipath activity was in that sector. This is shown schematically in Figure 3 by three paths in the northwest, one of which (path 1) carried the strongest Siple signal (as discussed in connection with Figures 1 and 2).

At 1120 the bearing trace fluctuated rapidly over a wide range. Inspection of expanded records suggested that two or more signals of comparable intensity were present during much of that interval and that the conditions for reliable DF analysis were therefore not fulfilled.

At 1125 the bearing record showed a strong southeast component, modeled in Figure 3 as path 2 and a nearby path. A concentration of activity in the southeast continued until the 1140 run, when a return to the northwest bearing was observed. Some of the scatter in the records, particularly at 1130 and 1140, is due to switching back and forth between widely spaced arrival bearings, including the bearing of path 2 in Figure 3.

Figure 5 helps to clarify these effects by showing DF measurements on selected signals that exhibited single path characteristics (see earlier discussion) during the period 1100-1230 UT. The format is similar to that of Figure 4, but the bearings have been rotated through -18° so as to place them in geographic coordinates. The groups of measurements that correspond to paths 1, 2, and 3 or their near neighbors in bearing are marked accordingly.

Below the bearing data are indications of the times of power line radiation (PLR) activity and of periods when DF data were not available. The transmitter was operated with only a few interruptions of less than 1 min over the 1100-1230 UT period. Following 1200 UT the transmitter format was less suitable for TR/DF analysis; hence the number of data were reduced in that period.

The scatter in the path groups is believed to be related to the problems of small bearing differences noted in connection with Figure 2, as well as to small-amplitude, relatively fast temporal variations in bearing (see below). Multipath activity on a fine scale has not been resolved; however, several measurements that

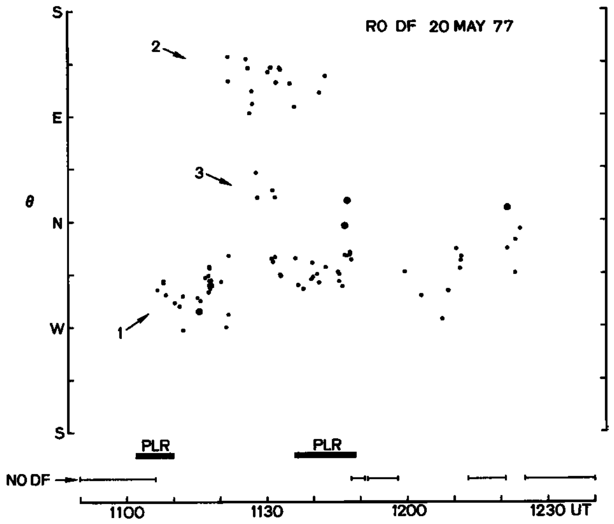

Fig. 5. Plot of arrival bearing (in geographic coordinates) versus time during a ~90-min period on May 20, 1977. The data points represent bearings on signals with single-path characteristics, evidenced by separation from other signals on frequency-time spectrograms. Data groups identified with paths 1, 2, and 3 of Figure 3 are marked. Illustrative cases of propagation on a secondary path with bearing close to that of a principal path are circled.

clearly represented secondary paths within the principal groups are circled. Gradual poleward (northward) trends in the bearings for paths 1 and 2 of Figure 3 are suggested by the data of Figure 5 (also those of Figure 4). Given nominal path ranges of ~70 km, the observed angular displacements correspond roughly to northeasterly motions of ~10 m/s, in general agreement with reported quiet-day cross-L drift speeds [*Evans*, 1972; *Carpenter and Seely*, 1976].

Figure 5 shows that detectable signals from paths 1 and 2 overlapped in time at the beginning and ending of the 1120-1140 period, but it does not reveal the rapidity of the signal level changes or spectral variations on the various paths. Some spectral details associated with the bearing change from SE to NW are shown in Figure 6, which contains the Roberval spectrum and bearing data for the interval 1135-1140 UT. On the spectrum are Siple power step signals such as those illustrated in Figures 1 and 2, with 20-s gaps between the 30-s transmissions. Following 1138 these signals disappeared as the power to the Siple antenna reached the -16-dB step. At ~1136 a PLR event with a northwest bearing began and soon dominated the spectrum and bearing data. A period of transitional flucatuations in bearing lasted only about 1 min between ~1136 and 1137.

Evidence of a close relation between this PLR activity and both Siple and natural signals is shown in Figure 7. These events were recorded as the PLR activity continued into the 1145-1150

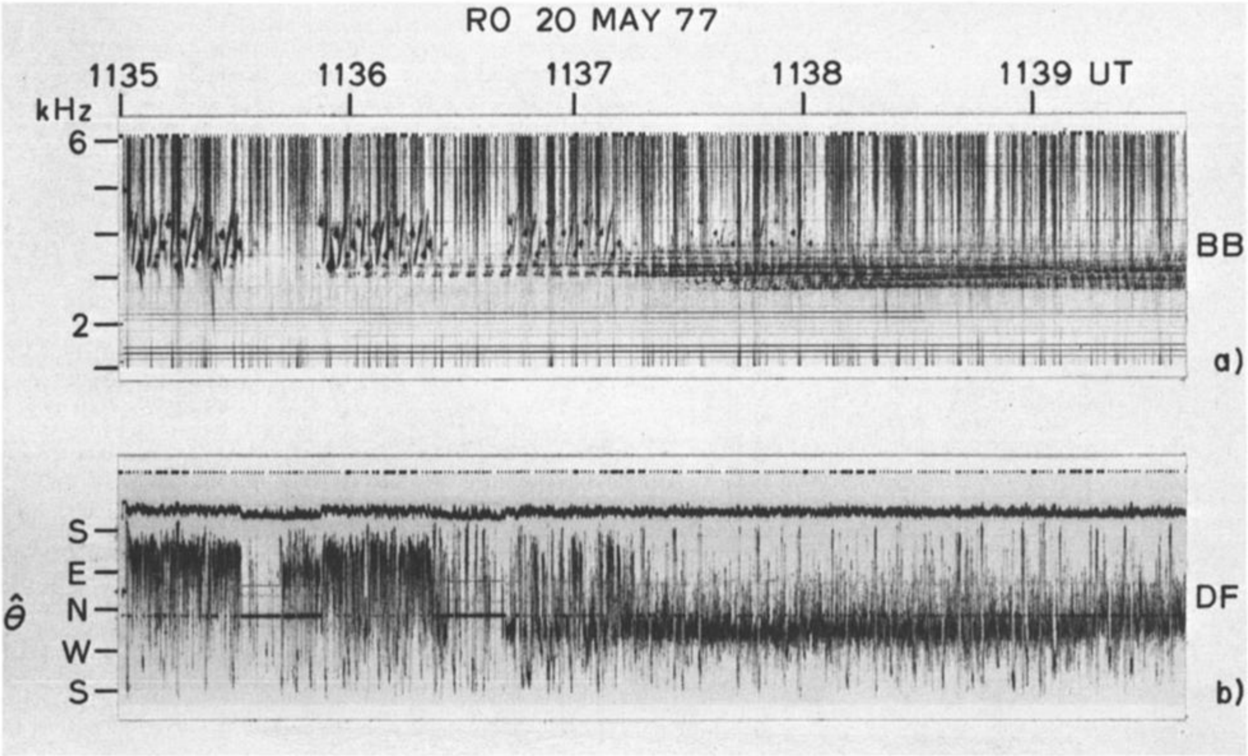

Fig. 6. Spectrograms showing the Roberval broadband wave activity and direction-finding information at the time of a shift from southeast to northwest in the principal arrival bearing activity. The upper record shows 30-s segments of Siple transmitter activity as the transmitter power was progressively reduced in steps of 4 dB. Near 1136 UT a power line radiation event began. See the text for further details.

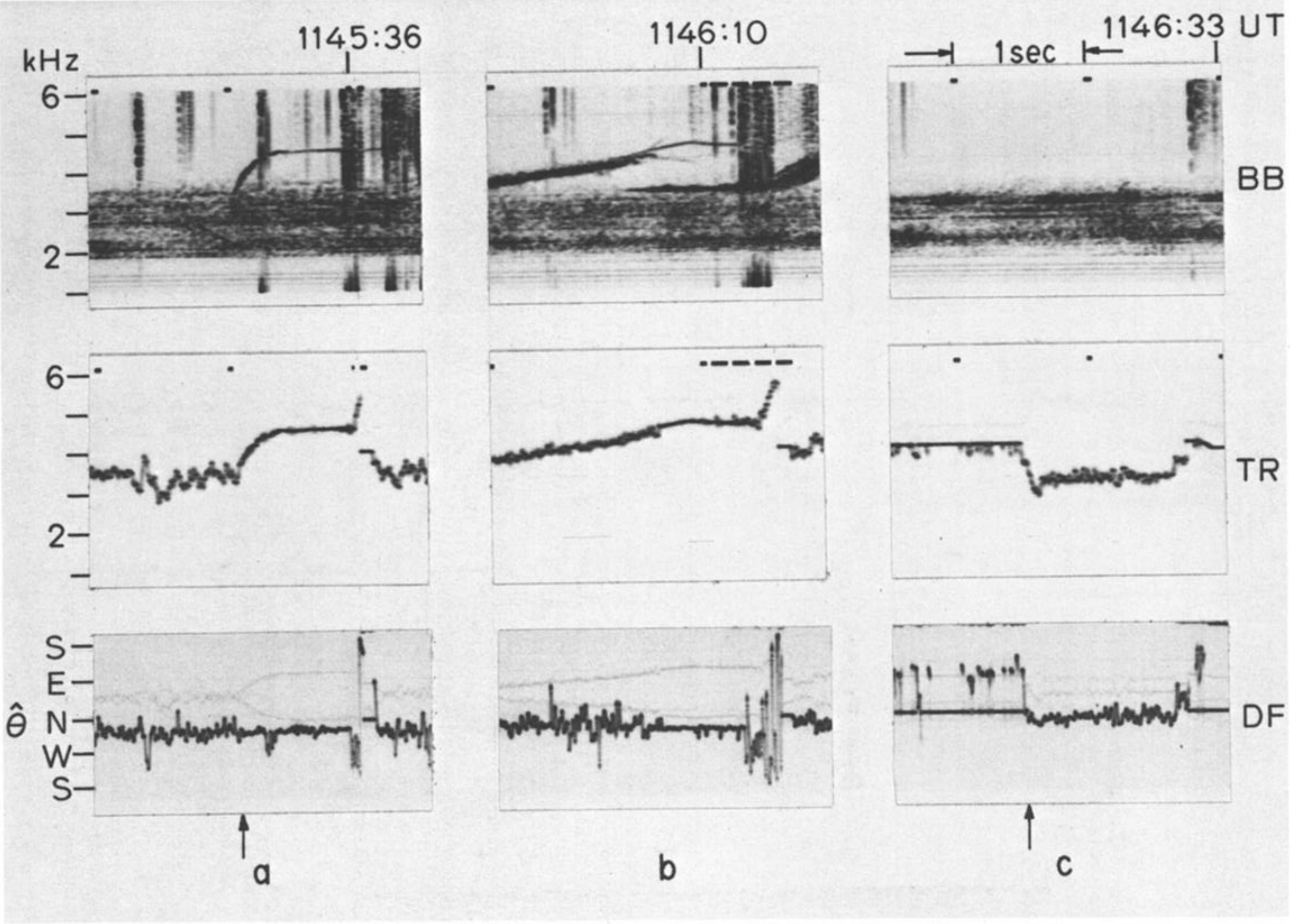

Fig. 7. Spectrograms in the format of Figures 1 and 2 showing direction-finding information on various types of events within a 1-min period. (a) Power line radiation activity and the upper part of a whistler with a triggered emission. (b) A Siple transmitter frequency ramp, followed by a triggered emission. (c) Power line radiation activity. See the text for further details.

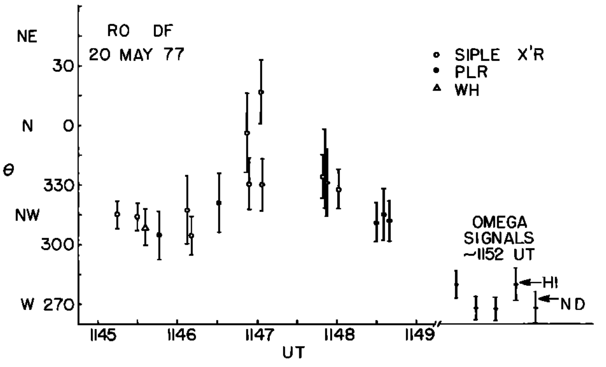

Fig. 8. Measurements in geographic coordinates of the arrival bearing of a sequence of signals over a several-minute period on May 20, 1977. The two bearings near north at ~1147 UT represented a secondary path. The data suggest a quasi-sinusoidal variation in arrival bearing for the principal path followed by Siple transmitter signals, power line radiation activity, and whistlers. Bearings on subionospherically propagating Omega signals are shown at the lower right.

UT period. Prior to the arrow in the lower margin of Figure 7a and following the arrow below Figure 7c the tracker followed portions of striated PLR noise forms. In both cases the bearing agreed within ~10° with the bearing of a whistler (Figure 7a) and a Siple signal and emission (Figure 7b).

An example of relatively fast, several-minute fluctuations in bearing within a ~20° range is illustrated in Figure 8, which provides an expanded view of activity in the interval 1145-1149 UT. The measurements are those displayed in Figure 5, augmented by results from PLR examples such as those of Figure 7. The average and standard deviation of the bearings, which were typically sampled at ~50 ms intervals within events ~1 s long, are plotted. The data are believed to represent the path carrying the strongest signals; the two bearings near 0° and 15° at ~1147 are interpreted as representing other paths.

Also displayed (lower right) are bearing measurements on subionospheric signals from the 11.3- and 10.2-kHz Omega transmitters in North Dakota and Hawaii. Horizontal arrows indicate the expected great circle bearings.

In Figure 8 the bearing of the principal path appeared to fluctuate over ±~12° with a period of ~4 min. The quasi-sinusoidal variation of the data is not understood. It may reflect a temporal modulation of propagation conditions between the lower boundary of the ionosphere and the 'ends' of magnetospheric ducts, whose guidance properties may not extend below ~2000 km under daytime conditions [Bernhardt and Park, 1977; Thomson and Dowden, 1978].

The fast changes in Siple and PLR signal amplitude on certain paths on May 20, 1977, suggests that PLR output from preexisting paths can 'switch on' or 'off' abruptly between times of the order of 1 min. Very clear examples of such fast level changes were observed on July 26, 1977, during transmission of constant frequency 2-s pulses every 10 s at constant transmitter power. Figure 9 shows a plot of average signal strength in each successive Siple pulse or associated triggered emission during a 13-min period. The measurements were made within a 1000-Hz band centered on the 2.5-kHz frequency of the Siple pulses and thus do not provide information on the higher-frequency parts of rising triggered emissions.

The signal level is at first relatively low and near the noise level, which was controlled by local power line interference. At ~1128:30 there was a sudden increase in field strength by ~10 dB within ~10 s. The activity continued near the higher level for several minutes and then exhibited further fast and relatively deep fading.

The directional data on this day were complicated by apparent polarization error effects and are not displayed. They do suggest a succession of directional shifts among multiple paths, however, with shifts tending to occur at the times of the larger changes in received signal level.

A preliminary study was made of the one-hop whistler activity at Siple Station during the May 20, 1977, period discussed above. The whistlers exhibited complex multipath structure, whose detailed features fluctuated in appearance on a time scale of the order of 5 min. Some of the changes in form coincided with major changes in Siple signal bearing at Roberval, but a detailed relationship has not yet been established between the two types of measurement.

The ~0.4-s spread in Siple signal travel times on May 20 is attributed primarily to longitudinal density gradients in the magnetosphere at $L = 4$. The whistlers to which the Siple travel times were compared showed clear evidence of longitudinal density structure, that is, relatively wide separation in travel time near a common nose frequency. From an analysis of the whistler and DF data and from previous studies of Siple signal path locations the density was inferred to vary by a factor of ≃30% over the east-west extent of the path 1 group of Figure 3, which was estimated to be ≃100 km.

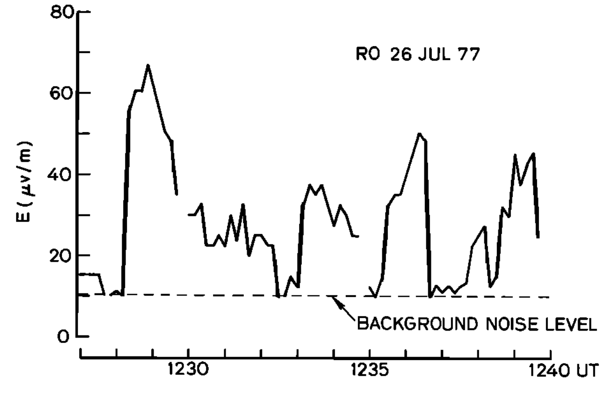

Fig. 9. Time variations in the amplitude of Siple transmitter signals received at Roberval on July 26, 1977, illustrating fluctuations of the order of 10 dB within periods of tens of seconds. Measurements were made on the average amplitude of 2-s pulses transmitted at constant transmitter power every 10 s. See the text for further details.

4. Discussion and Concluding Remarks

The data suggest that when a set of slowly drifting whistler ducts is illuminated by the Siple VLF transmitter or by a source of power line radiation, there can be fast (~10-1000 s) variations in the amplitude and apparent arrival bearing of the magnetospherically propagated signals.

The sequence of bearing changes observed over the course of ~1 hour on May 20, 1977, may have reflected the eastward gradient-curvature drift motion of low-energy electrons through the pattern of whistler ducts. While the presently available data are not sufficient as a basis for modeling details of the particle structure and motion, the following qualitative picture of the situation is offered. The presence of a 'source' cloud of interacting electrons to the west of Roberval prior to ~1120 UT was suggested by the original concentration of Siple signals on path 1 of Figure 3 in that period. A PLR event, also on path 1 of Figure 3, was observed between 1102 and 1109 UT. After the PLR event decayed, the Siple activity continued on path 1 (see Figure 5), presumably because of its larger injected signal. Shortly after 1120 UT, Siple began to excite paths to the east of Roberval (see Figure 5), and for a few minutes there was strong excitation on both path 1 and path 2 of Figure 3. Then after 1125 UT, path 1 was observed only sporadically, and activity was centered to the east of the station until ~1136, when a new source of electrons appeared to the west of Roberval. At that time an intense PLR event developed rapidly on path 1, and during the next high-power Siple transmission, a few minutes later, there was a return to strong Siple activity on path 1. The PLR, probably because of source weakness, was again restricted to path 1, while Siple continued to produce signals to the east on path 2 (see Figure 5) under the continuing but apparently waning influence of the first 'cloud.'

The possibility that the ground data are providing a crude 'image' of drifting particle structure is also suggested by the rapidity of the reported amplitude variations. This rapidity (~10-100 s) may be associated with the 'threshold' effect recently reported by Helliwell [1979] and more fully by Helliwell et al. [1980] from observations of the magnetospheric response to stepping the Siple transmitter in power (as was done on May 20, 1977). A transition from no apparent temporal growth to fast temporal growth of coherent signals was observed within a narrow (a few decibels) range of injected signal levels. Furthermore, it was found that the threshold power level could change by up to ~20 dB from observing day to day and could vary with time somewhat more narrowly within a several-hour observing period. It is believed that the fast amplitude changes reported here represent a particular aspect of the phenomenon reported by Helliwell et al. Stress here has been on the threshold effect under conditions of constant wave level and varying interacting particle flux, in contrast to the conditions of varying wave level (and presumably constant particle flux) described by Helliwell et al.

Dispersion analysis of whistlers and Siple pulses observed on May 20, 1977, provides a basis for estimating the parallel energy of electrons in cyclotron resonance with the Siple pulses near the equator. This energy is ~500 eV, and assuming particle pitch angles near ≈50°, a total particle energy of ~1-2 keV is then estimated. For such particles the eastward gradient-curvature drift at L ~ 4 corresponds to a velocity of the order of 50 m/s at ionospheric heights, or 180 km/h. While this velocity does not explain the timing of the arrival bearing changes discussed above, it does not appear to be inconsistent with them.

The eastward drift of fine structure in the low-energy electrons, coupled with the threshold effect, may help to explain the rapidity of the reported temporal variations in signal amplitude. At 50 m/s a sharply defined feature of the electrons could drift ~6 km within ~2 min. If not a significant fraction of a duct's longitudinal dimension, this distance could nevertheless be comparable to the width of an emission generation region within a duct, as Raghuram [1977] has suggested.

Variations in propagation conditions must also be considered as a basis for explaining the data. If the particle source hypothesis is borne out by further measurements, waves from VLF transmitters and PLR sources would appear to have increased promise as a means of 'imaging' particle source activity in the outer plasmasphere during relatively quiet magnetic conditions. This imaging could be viewed as an extension of the way in which natural VLF chorus near L = 4 has been found to mirror energetic particle injections and drifts observed at synchronous orbit under more disturbed conditions [Park et al., 1979; Thomas, 1979].

It is now clear that the manner in which the ionosphere is illuminated by downcoming signals originating in a low-power VLF source is more variable in time than might have been predicted from earlier work with whistlers. Interestingly, recent work (in progress at Stanford) with relatively low latitude whistlers propagating near L = 2.3 to Palmer Station, Antarctica, shows a degree of time stability in whistler arrival bearing that is consistent with earlier observations. It is clearly of interest to further investigate these various propagation regimes, so as to better describe the interplay in the magnetosphere between propagation and wave-particle interaction effects.

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References

Angerami, J. J., Whistler duct properties deduced from VLF observations made with the OGO-3 satellite near the magnetic equator, J. Geophys. Res., 75, 6115, 1970.

Bernhardt, P. A., and C. G. Park, Protonospheric-ionospheric modeling of VLF ducts, J. Geophys. Res., 82, 5222, 1977.

Carpenter, D. L., and N. T. Seely, Cross-L plasma drifts in the outer plasmasphere: Quiet-time patterns and some substorm effects, J. Geophys. Res., 81, 2728, 1976.

Evans, J. V., Measurements of horizontal drifts in the E and F regions at Millstone Hill, J. Geophys. Res., 77, 2341, 1972.

Helliwell, R. A., Siple Station experiments on wave-particle interactions in the magnetosphere, in Wave Instabilities in Space Plasmas, edited by P. J. Palmadesso and K. Papadopoulos, p. 191, 1979.

Helliwell, R. A., and J. P. Katsufrakis, VLF wave injection into the magnetosphere from Siple Station, Antarctica, J. Geophys. Res., 79, 2511, 1974.

Helliwell, R. A., D. L. Carpenter and T. R. Miller, Power threshold for growth of coherent VLF signals in the magnetosphere, J. Geophys. Res., 85, in press, 1980.

Leavitt, M. K., A frequency-tracking direction-finder for whistlers and other very-low-frequency signals, Tech. Rep. 3456-2, Stanford Electron. Lab., Stanford Univ., Stanford, Calif., 1975.

Leavitt, M. K., D. L. Carpenter, N. T. Seely, R. R. Padden, and J. H. Doolittle, Initial results from a tracking receiver/direction finder for whistler mode signals, J. Geophys. Res., 83, 1601, 1978.

Park, C. G., C. S. Lin, and G. K. Parks, A ground-satellite study of wave-particle correlations, submitted to J. Geophys. Res., 1980.

Raghuram, R., Suppression effects associated with VLF transmitter signals injected into the magnetosphere, Tech. Rep. 3456-3, Stanford Electron. Lab., Stanford Univ., Stanford, Calif., 1977.

Seely, N. T., Whistler propagation in a distorted quiet-time model magnetosphere, Tech. Rep. 3472-1, Stanford Electron. Lab., Stanford Univ., Stanford, Calif., 1977.

Thomas, T. W., Substorm-related VLF chorus events: Local time dependence and relationship to newly-injected clouds of drifting energetic electrons, Ph.D. thesis, Radiophys. Lab., Thayer Sch. of Eng., Dartmouth Coll., Hanover, N. H., 1979.

Thomson, R. J., and R. L. Dowden, Ionospheric whistler propagation, J. Atmos. Terr. Phys., 40, 215, 1978.

Tsuruda, K., and K. Hayashi, Direction-finding technique for electronically polarized VLF electromagnetic waves and its application to the low latitude whistlers, J. Atmos. Terr. Phys., 37, 1193, 1975.

Tsuruda, K., and M. Ikeda, Comparison of three different types of VLF DF techniques, J. Geophys. Res., 84, 5325, 1979.

Walker, A. D. M., The theory of whistler propagation, Rev. Geophys. Space Phys., 14, 629, 1976.

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