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Remote Sensing of the Magnetospheric Plasma by Means of Whistler Mode Signals

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Early in the past decade of U.S. Antarctic research, the whistler method of measuring equatorial electron density was found to agree with in situ satellite electron density measurements by a radio technique. Furthermore, the whistler method of measuring the east-west component of the convection electric field in the outer plasmasphere was found to agree, under conditions of mapping in a dipole magnetic field, with simultaneous results from incoherent scatter radar. A global model of the east-west convection electric field in the outer plasmasphere during substorms was developed. The detection of whistlers and their use for magnetospheric diagnostics have been important elements in recent studies of burst precipitation into the ionosphere induced by whistlers and by other transient whistler mode waves propagating in the magnetosphere. Whistlers have also been used to obtain data on the L values and equatorial electron densities associated with the propagation paths of signals from the Siple VLF transmitter. The process of untrapping of downcoming wave energy from ducts in the upper ionosphere and the upward repropagation of portions of the energy following reflection in the lower ionosphere lead to the excitation of adjacent ducts as well as to upward propagation in the nonducted mode. Efficient interduct coupling has been found to occur over north-south ionospheric distances of >1000 km. Studies of the outer limits of observed ducting revealed dayside path radii in the range 6-8 R_E and nightside limits of ~5.5 R_E. Ducted propagation beyond the plasmapause was found to occur regularly in the 0000-1800 MLT time range, but with variable rates and at various locations with respect to the plasmapause position. The special features of this propagation are believed to be related to conditions of lightning excitation, ionospheric penetration, and wave-particle interactions that are special to the region beyond the plasmasphere. New aspects of Siple wave injection experiments were demonstrated by the application of a new phase measurement method to Siple signals that did not exhibit fast temporal growth during passage through the magnetosphere. This method, a refinement of techniques developed previously by New Zealand workers, is capable of detecting fluctuations in phase path with period of ~10 s and greater and thus can be used to study magnetospheric convection and coupling fluxes along field lines of propagation as well as pulsations associated with ultralow-frequency perturbations of the geomagnetic field. Additional topics discussed include results from direction-finding experiments and evidence of the dependence of whistlers upon magnetospheric wave amplification.

1. INTRODUCTION

This review concerns the past decade of U.S. Antarctic research, in which very low frequency (VLF) whistler mode signals (~ 1 – 30 kHz) received at ground stations have been used to study the magnetospheric plasma. We emphasize diagnostics of the thermal plasma and of whistler mode propagation therein, but also remark briefly on hot plasma effects that are detectable by whistlers. We discuss research results obtained by applying a variety of VLF probing methods, but will refer the reader to the literature for detailed information on the probing methods themselves. A previous topical review on U.S. Antarctic VLF research by *Park and Carpenter* [1978] summarizes earlier results from whistler probing and discusses whistler-probing methods. The literature contains a number of discussions of topics relevant to the interpretation of whistler data, examples from the past decade being articles by *Tarcsai and Daniell* [1979], *Strangeways* [1980, 1982], and *Daniell* [1986*a*,*b*].

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2. INTERCOMPARISON OF RESULTS FROM WHISTLERS WITH DATA FROM SATELLITES AND INCOHERENT SCATTER RADAR

2.1. *Equatorial Electron Density Profiles*

During the International Magnetospheric Study (IMS) year of 1978, data from multiple whistler paths were for the first time compared to in situ satellite measurements along an eccentric, near-equatorial orbit [*Carpenter et al.*, 1981]. Figure 1 shows one of three comparisons of data from the University of Iowa sweep frequency receiver on ISEE 1 with equatorial electron density values determined from whistlers recorded at Siple ($L \sim 4.3$) and Palmer stations ($L \sim 2.3$), Antarctica. Good agreement between the methods was found in all three cases meeting the observational requirements of multipath whistler occurrence and ISEE operations near the longitudes of Siple and Palmer and within ~ 20° of the magnetic equator. Calm to moderately disturbed magnetic conditions in the nightside magnetosphere were represented. Since a whistler component provides an equatorially weighted integral measure of the electron density along its path of propagation [e.g., *Carpenter and Smith*, 1964], one must assume a field-line plasma distribution model in the calculations for purposes of esti-

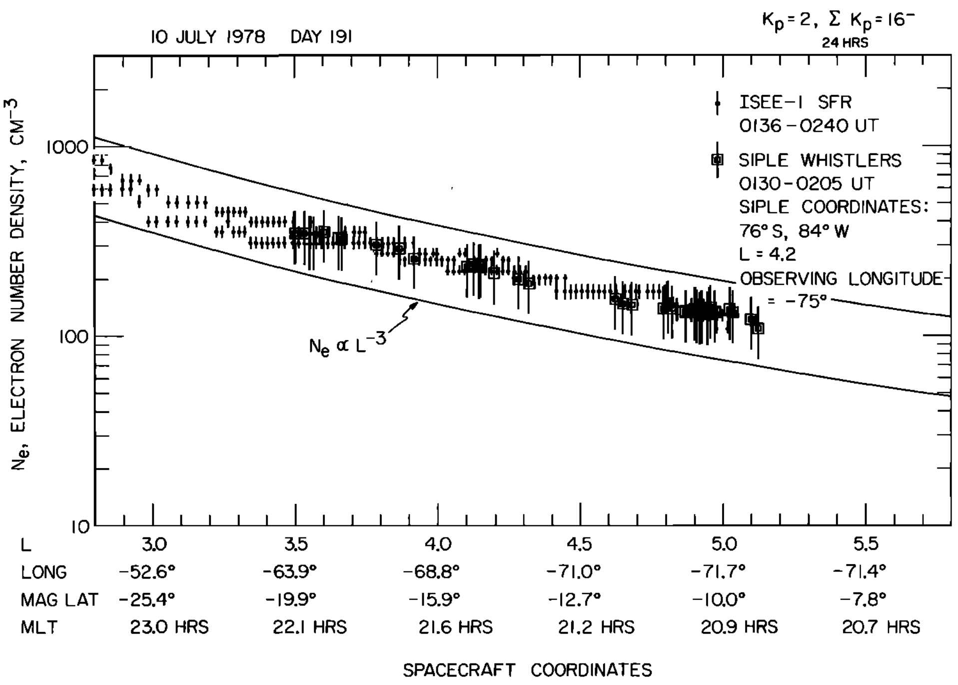

Fig. 1. Comparison of electron densities in the magnetosphere determined from whistlers recorded at Siple Station, Antarctica, and from sweep frequency receiver data on the ISEE 1 spacecraft. The data represent the premidnight plasmasphere under quiet magnetic conditions. From *Carpenter et al.* [1981].

mating electron density at any particular location. The successful comparisons with in situ data provided support, additional to that found earlier by *Angerami* [1970], for use of a diffusive equilibrium model [*Angerami and Thomas*, 1964; *Park*, 1972] to approximate the field line distribution. A true state of diffusive equilibrium in the outer plasmasphere is probably approached only rarely, in view of the repeated cycles of erosion, drainage, and replenishment that occur in that region [e.g., *Park*, 1970; *Chappell*, 1972; *Horwitz et al.*, 1981; *Singh and Hwang*, 1987].

Good agreement of the multipoint whistler measurements with the ISEE profiles indicated that the densities within the whistler ducts differed from interduct densities by less than 30%, thus placing any density enhancement factors associated with the ducts within a range envisioned by earlier propagation theory [*Smith*, 1961]. This finding was also in agreement with the earlier work of *Angerami* [1970], who concluded from a combination of ground and OGO 3 satellite whistler data that the density enhancements in plasmaspheric whistler ducts near $L = 4$ generally lie between 6% and 22% and rarely exceed 33%. It thus appears that at least for $L > 3$, the restriction of whistlers to ducts, presumably of slightly enhanced ionization density, does not invalidate their use to describe the average density of the nearby plasmasphere.

2.2. *Cross-L Plasma Drifts*

During the IMS, the first direct comparisons were also made between results on cross-L plasma motions from whistlers and from incoherent scatter radar data [*Gonzales et al.*, 1980]. Remarkably, the period of observation included the interval of ground-whistler/satellite density comparisons illustrated in Figure 1. Figure 2 shows the northward and eastward components of ionospheric electric field determined by the radar (top and middle panels) and the eastward component of electric field at the equator inferred from the cross-L motions of whistler ducts. The radar data, obtained at Millstone Hill, represent $L = 4.4$, while the whistler data, recorded at Siple, Antarctica (conjugate to Roberval, Canada), represent an average of results for paths in the L range 3.5–4.7. The eastward electric field amplitude scales differ by a factor of 10 so as to approximately account for the magnetic field mapping factor between the ionosphere and the equator [*Mozer*, 1970].

The eastward fields show good agreement in the field direction over a 12-hour period and, except near 0400 UT, suggest efficient mapping of the fields from the equator to the ionosphere. The good agreement of the radar and whistler data during the isolated substorm near 0800 UT, in terms of mapping in a dipole-like field, was found to be consistent with an essentially curl-free condition of the electric field in the outer plasmasphere, and with essentially zero potential drop along the field lines of observation, at least on the time scale of 20 min over which the radar and whistler data were averaged. The inference of zero potential drop was independently supported by the prolonged observation of particular whistler components that were assumed to have followed magnetospheric ducts. The guiding properties of the ducts (at least down to the upper ionospheric limits of ducting action [e.g., *Bernhardt and Park*, 1977]) were not expected to persist in the presence of significant shears in transverse drift velocity associated with potential drops along the field.

Data from the double probe on ISEE were acquired prior to the substorm in the high-altitude region probed by the whistlers [*Maynard et al.*, 1983]. On a time scale of 20 min, the satellite results near $L = 4$ were in good agreement with the whistler and radar data.

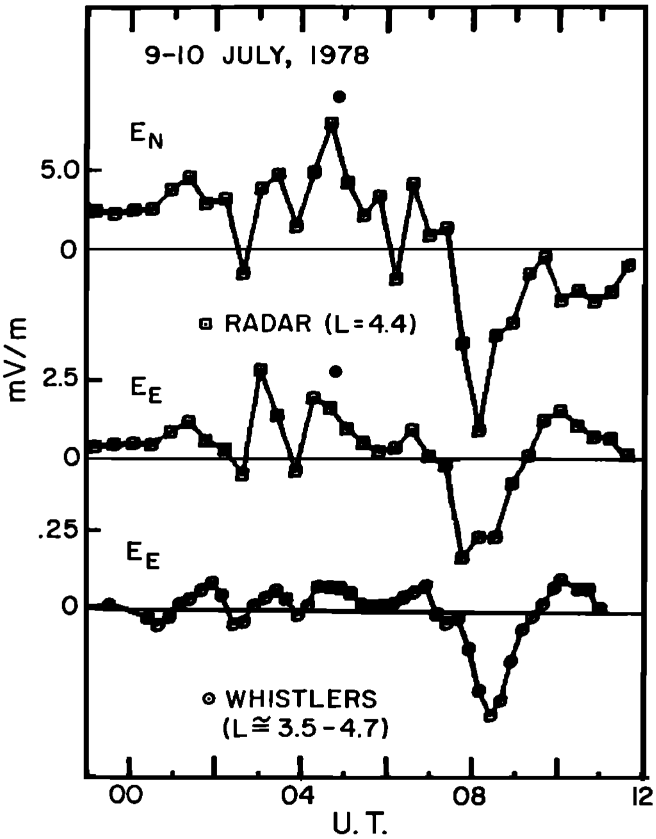

Fig. 2. Comparison of northward and eastward electric fields in the ionosphere at $L = 4.4$ (upper panels) with the eastward electric field at the equator, deduced from whistlers propagating near the meridian of the Millstone Hill radar. The eastward field amplitude scales differ by a factor that accounts for the magnetic field mapping factor between the ionosphere and the equator. From *Gonzales et al.* [1980].

2.3. *Substorm Cross-L Convection Model for the Outer Plasmasphere*

Thirty four case studies of cross-L motions of whistler paths were used by *Carpenter et al.* [1979] as the basis of a descriptive model of cross-L convection in the outer plasmasphere during substorms, and therefore of the substorm-associated east-west component of the convection electric field. The data were acquired at Eights, Byrd, and Siple, Antarctica, in the period 1963-1975. Temporal variations were not included, and certain observed spatial features tended to be obscured by the averaging used, but the model was believed to be representative of the major spatial features of the substorm east-west field in the outer plasmasphere with periods of ≥ 30 min. The whistler model was recently invoked by *Newell and Meng* [1986] as part of an explanation of the introduction of observed ≤ 1-keV magnetospheric ions into the inner plasmasphere during substorms.

3. The Role of Whistlers In Other Magnetosphere/Ionosphere Probing Experiments

3.1. *Studies of Wave-Induced Particle Precipitation From the Magnetosphere*

In recent years there has been a developing scientific interest in the phenomenon of burst particle precipitation associated with the propagation of whistler mode wave transients in the magnetosphere. This important topic has been discussed in a number of recent papers [e.g., *Inan and Carpenter*, 1987; *Inan et al.*, 1988]; here we limit ourselves to a few remarks about the waves associated with observed precipitation events.

When burst precipitation events involving electron energies above 50 keV occur within the dense plasmasphere, any correlated waves observed at ground stations are usually whistlers that have well-defined frequency-versus-time or dispersion characteristics, and display only limited evidence of triggering of VLF emissions [*Carpenter and LaBelle*, 1982; *Inan and Carpenter*, 1987]. This simplicity facilitates study of individual wave-associated precipitation events, in that whistlers are readily recognized and have well-defined times of origin, knowable to within about ±10 ms in the many cases in which the causative impulse is identifiable on the broadband records, or to within ~ ±50 ms if only the whistler itself is available [*Ho and Bernard*, 1973]. From the dispersion properties of the whistlers, it is frequently possible to obtain information on whistler path L values and electron density for use in computer simulations of the particle-scattering process [*Chang and Inan*, 1985]. Also available is the received whistler amplitude spectrum, from which it is possible, subject to certain assumptions, to estimate the amplitude spectrum in a hypothesized high-altitude interaction region [e.g., *Inan et al.*, 1985]. In computer simulations one can then employ a wave train with an instantaneous distribution in space that is quite well constrained by observations, certainly more so than in most cases in which the driving waves are assumed to be VLF emissions.

Burst precipitation events detected poleward of the plasmapause are often associated with whistlers [*Rosenberg et al.*, 1971; *Foster and Rosenberg*, 1976; *Helliwell et al.*, 1980; *Dingle and Carpenter*, 1981; *Hurren et al.*, 1986], but in these cases the whistler usually triggers a strong and often seconds-long burst of VLF emissions, which may dominate the scattering process. Such cases are more difficult to model, but retain the whistler-associated benefit of access to information on propagation path parameters, as well as information, based upon the evidence of triggering by the whistler, concerning the time interval within which the emissions were triggered.

In many cases occurring poleward of the plasmapause, a whistler is not detected, and the wave activity is dominated by discrete VLF "chorus" emissions. Identification of correlated wave bursts may then be difficult, due in part to the presence on f-t records of additional chorus elements that propagate on paths with ionospheric endpoints outside the range of the local observations of precipitation effects. However, on occasion the multipath effect has been found to be minimal, and individual noise elements have been correlated with specific precipitation events registered by ionospheric sensors [*Armstrong et al.*, 1984].

3.2. *Whistlers as a Source of Information on the Propagation Paths of Siple Transmitter Signals*

Signals from the experimental VLF transmitter at Siple Station [see *Helliwell*, this issue] often propagate on one or more active whistler paths. The L values of the paths can in many such cases be inferred by matching the Siple signal travel times at one or more transmitter frequencies with the travel times of the multiple whistler components at those frequencies, and then doing a conventional path analysis on the whistlers [*Carpenter and Miller*, 1976]. The relatively narrow frequency bands (~1 kHz wide) to which most Siple f-t transmitter formats are limited complicate efforts at dispersion analysis based entirely upon signal travel times at multiple transmitter frequencies. However, on some occasions when wider frequency ramps are transmitted, it is possible to obtain dispersion information comparable to that in a well-defined whistler [*Carlson et al.*, 1985].

Whistler analysis has been applied to Siple data acquired during 1973-1974 operations at transmitter frequencies near 5 kHz [*Carpenter and Miller*, 1976] and during 1980 operations with a second-generation transmitter at frequencies that were mostly in the range 2.5-3.5 kHz [*Carpenter and Bao*, 1983]. From the whistler data it was possible to show that in both periods the path L range of well-defined signal reception corresponded to an approximately 200-300 km north-south range at ionospheric heights [*Carpenter and Miller*, 1976], which is limited compared to the range of ~ 1000 km observed in many multipath whistlers.

It was also possible to conclude that while the lower-frequency transmissions in 1980 tended to be concentrated on paths with entrance points centered overhead the station, the higher-frequency signals (1973–1974) tended to propagate on paths centered slightly equatorward of Siple [*Carpenter and Bao*, 1983]. This could be understood as the result of the half-equatorial gyrofrequency cutoff for ducted whistler propagation [*Smith*, 1961; *Carpenter*, 1968]; signals near 5 kHz tended to be above the propagation limit on paths overhead Siple, while this was not the case for the lower frequencies. Further, the whistler analysis, by revealing the signal path and hence the equatorial gyrofrequency f_{Heq}, made it possible to obtain statistics on the ratio of transmitter frequency f_{tr} to f_{Heq}, which is important in estimating the energies of gyroresonant interactions that can be expected for waves transmitted at particular frequencies.

4. Whistler Studies of Geomagnetic-Field-Aligned Propagation "Ducts" And Their Excitation by Ground Sources

4.1. *Interduct Coupling*

The observed f-versus-t or dispersion properties of whistlers imply that such signals propagate to middle-latitude ground stations along a set of discrete geomagnetic field-aligned "ducts" whose propagation characteristics are essentially constant over periods of minutes to tens of minutes. The observed f-versus-t curve of an individual whistler component has been found to agree with theoretical predictions of quasi-longitudinal propagation within a duct of enhanced ionization [*Smith*, 1961], and in cases of echoing back and forth along a particular path, the successive intervals between appearances of the signal at an observing frequency have been found to be identical within < 1% experimental accuracy.

Figure 3*a* shows a diagram of a downcoming multicomponent whistler that has propagated in three magnetospheric ducts. In this idealized case, each component undergoes (1) untrapping from the magnetospheric duct in the topside ionosphere, (2) partial reflection from the bottomside ionosphere, (3) retrapping of reflected energy in the original duct, and (4) penetration of the ionosphere and reception at a ground receiver. This highly simplified model, combined with information on the time of origin of the whistler, provides a basis for recognizing the phenomenon of interduct coupling, in which there is transfer of energy between ducts at the time of reflection at one or another of the ionospheric endpoints of the path [e.g., *Smith and Carpenter*, 1982]. The effect is shown schematically in Figure 3*b*, where the reflected waves from individual ducts illuminate both the original and the adjacent ducts.

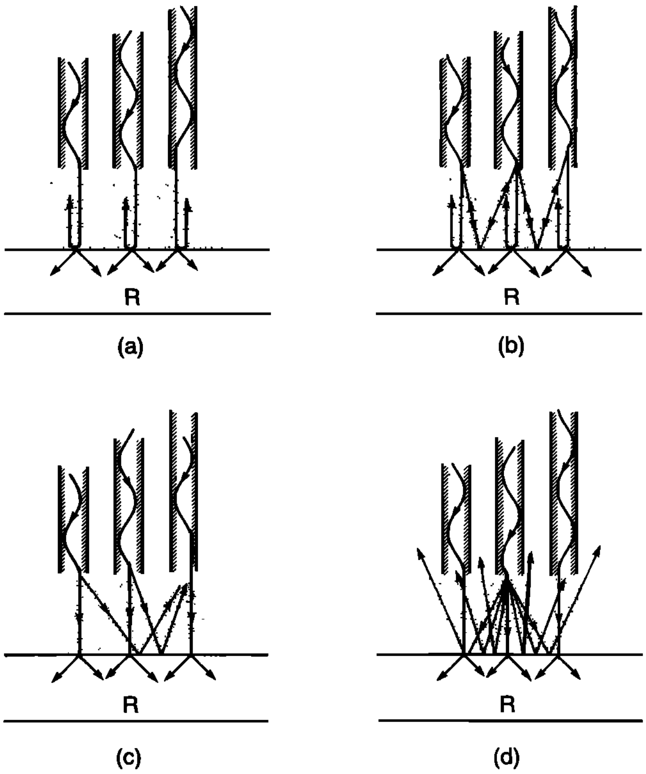

Fig. 3. Diagrams showing various types of coupling among multiple discrete magnetospheric whistler mode paths at the time of wave reflection from the bottomside of the ionosphere. A portion of the wave energy from each path penetrates the ionosphere and is received at R. (*a*) Case dominated by reexcitation of the original paths by reflected waves. (*b*) Case of reflected waves exciting both the original and the adjacent ducts. (*c*) Case dominated by reexcitation of a single active duct by waves from both the active duct and other ducts. (*d*) Case of reflected waves exciting both nearby ducts and regions of nonducted propagation.

Interduct coupling has long been known; *Morgan et al.* [1959] reported a whistler echoing situation in which travel times from the lightning origin not only were multiples of one hop delays along the individual paths, as in Figure 3*a*, but also exhibited combinations of one-hop delays involving more than one path. Furthermore, it has long been recognized that two-hop whistlers observed at middle latitudes are not usually simple replicas of one-hop events, with all travel times multiplied by 2. While two-hop travel times tend on average to be twice those of the one-hop events, the two-hop whistler is often diffuse, as if there had been coupling or "path mixing" among many closely spaced paths at the time of one-hop reflection.

Since the effects of interduct coupling only begin to develop following the first hop of the whistler, one-hop signals are preferentially used in many diagnostic situations, and the full extent and implications of the spreading of energy during reflection have only recently begun to be appreciated. The spreading effect has been increasingly recognized both in regard to the role of whistlers in magnetospheric wave-particle interactions, and in studies of magnetospheric wave propagation as observed on satellites [e.g., *Rastani et al.*, 1985]. When multihop whistler echoing is observed at ground stations, a single most active whistler path can often be identified, on which losses appear to be minimum and on which VLF emissions, some directly triggered by the whistler, also propagate. In such a case, energy from all or most of the one-hop paths couples into the active path after the initial hop and then continues to propagate along that path. The coupling is shown schematically in Figure 3*c*. The result is a series of echoes, each of whose total duration at any frequency (from first to last element within the echo) is limited to (or less than) the total duration of the first hop of the whistler at that frequency. It was recently found that efficient coupling of the kind illustrated in Figure 3*c* can take place between ducts separated by as much as ~1500 km at ionospheric heights [*Carpenter and Orville*, 1987] and that coupling can occur from a path inside the plasmasphere to one outside [*Smith and Carpenter*, 1982; *Carpenter et al.*, 1986]. In the less common cases in which two or more paths are "active", the temporal spread of successive echoes tends to increase in proportion to hop number, and individual path combinations such as those reported by *Morgan et al.* [1959] may be identified.

In satellite studies it has been found that much of the discrete signal activity observed at relatively high altitudes inside $L \sim$ 6-8 reaches the satellite as unducted waves that have reflected at low altitudes following ducted propagation [*Thomson and Dowden*, 1978; *Bell et al.*, 1983; *Smith et al.*, 1985; *Rastani et al.*, 1985]. This situation, which should probably be considered part of the most general case, is illustrated in Figure 3*d*. The implication is that natural and controlled signals propagating in ducts can strongly influence the wave spectra in magnetospheric regions that extend well beyond the spatial limits of the ducts themselves.

4.2. *Ducts as a Probe of Spatially and Temporally Varying Magnetospheric Conditions*

One would like to interpret the repeated detection of a particular whistler component as an indication that certain physical conditions, requisite to the existence of a whistler duct, have been fulfilled over the observing interval in question. Such conditions have not been well investigated but presumably would include an absence of significant field-aligned potential drops, as noted in the above-mentioned case study of cross-L path motions in the outer plasmasphere during a substorm. One would like to map the spatial limits of ducting as a function of time, as a means of remotely mapping the boundaries of magnetospheric regions in which the physical conditions for ducting obtain. Such mapping depends upon suitable wave activity as well as properly located receivers, and has been accomplished thus far to a limited extent only. Two relevant studies have been made in the last decade, one on whistler propagation at high L values during quiet conditions, and a second on whistler propagation outside the plasmapause.

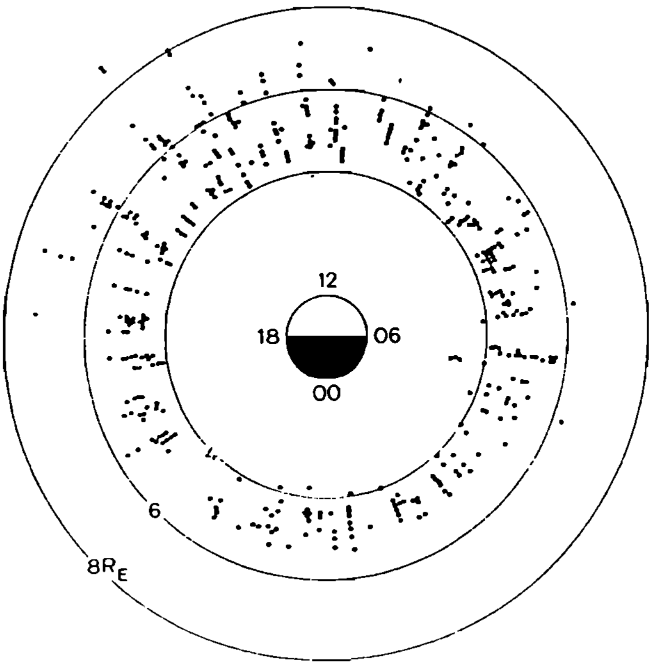

Fig. 4. Scatter plot of whistler path equatorial radii versus magnetic local time for the 6 quiet days July 2–4 and July 8–10, 1967. The plot includes hourly values of path radii observed beyond ~4 R_E. The whistlers were recorded at Byrd Station, Antarctica ($L \sim 7$). From *Carpenter* [1981].

4.2.1. *Observed limiting duct radii during quiet conditions.* When multipath whistler rates are sufficiently high and paths are excited in the vicinity of $L = 5$, it is possible from measurements of the lowest observed whistler nose frequency to estimate the maximum radius or L value of ducted whistler propagation for the observing period. In such a study it is helpful to have an observing station near $L = 6$, so as to minimize losses associated with propagation from path endpoints in the ionosphere to the receiver.

The high-latitude extent of ducted propagation was estimated using whistlers recorded during 6 magnetically calm days in July 1967 at Byrd, Antarctica ($L \sim 7$) [*Carpenter*, 1981]. A 20-km-long horizontal dipole antenna was used, and recordings were made for ~40 min each hour. Figure 4 is a scatter plot in coordinates of equatorial radius versus MLT of path equatorial radii observed beyond $L = 4$ on an hourly basis during the 6 days. In the post midnight sector the limiting radii were relatively well defined, near $L = 5.5$, while on the dayside they were generally larger, reaching afternoon maxima in the 6 to 8 R_E-range. Figure 5 shows spectrograms of a whistler with nose frequencies extending from above 2.5 kHz to a minimum of 670 Hz. Two examples, recorded within 1 min of each other near 1500 MLT, are shown to indicate the repeatability of the phenomenon. The path L value for the component with travel time ~ 6s and $f_n \sim$ 670 Hz was estimated to be 8.7 R_E according to *Seely's* [1977] corrections to a dipole analysis. This was the largest path radius observed in the study, or in any other study of which we are aware. The equatorial electron density was inferred to be 13 el/cm^3 or el cm^{-3}. In most hours on the 6 days, the outermost whistler path radii were found

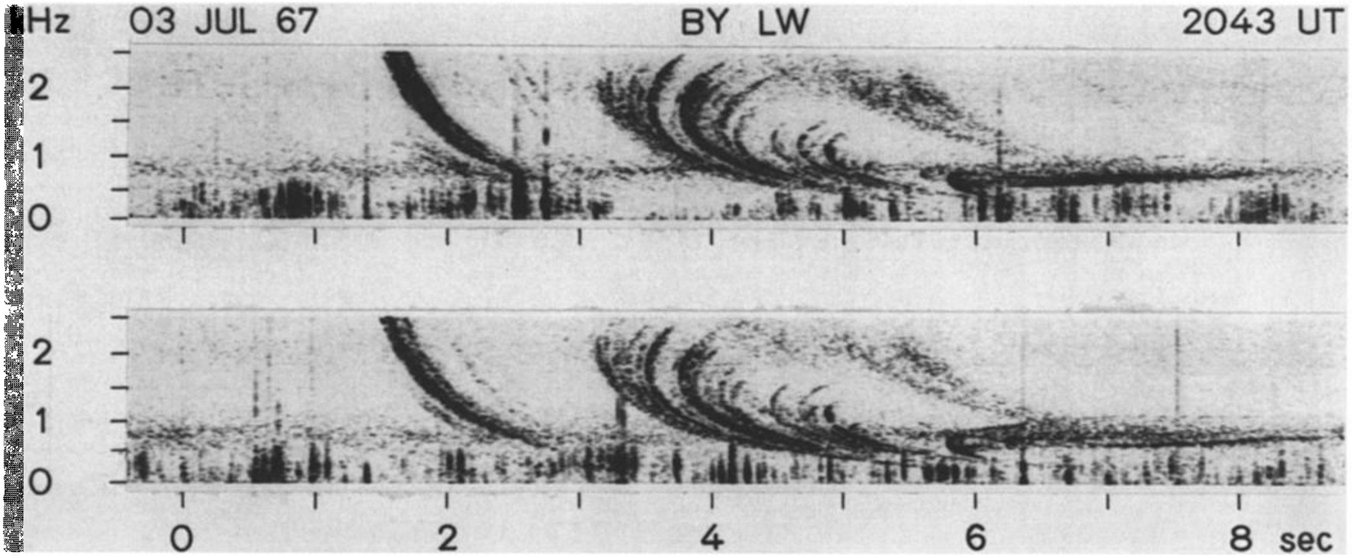

Fig. 5. Frequency-time records of two multicomponent whistlers propagating on paths extending to a maximum inferred radius of 8.7 R_E. The component with the lowest nose frequency, near 670 Hz, has a travel time near 6 s and appears to have triggered slowly rising emissions. Beginning at the top of the records near $t = 5$ s is a third-hop echo of the first prominent component. The events were recorded at Byrd Longwire Station within a ~1-min period near 1500 MLT on July 3, 1967. From *Carpenter* [1981].

to be within $\Delta R < 0.3$ R_E of a plasmapause-type density falloff, usually on its inner side.

4.2.2. *Ducted propagation outside the plasmapause.* Little has been published about this important topic. Confusion probably exists; whistlers propagating outside the plasmasphere have been found to be associated with burst particle precipitation detected by various methods [e.g., *Rosenberg et al.,* 1971; *Helliwell et al.,* 1980; *Dingle and Carpenter,* 1981; *Doolittle and Carpenter,* 1983], but at the same time, whistlers propagating outside the plasmasphere both to satellites [e.g., *Carpenter et al.*, 1968; *Koons*, 1985] and to some ground stations [*Woods et al.,* 1974] have been found to be rare.

To clarify this matter and provide new information, a study has been made of whistler data from Siple, Antarctica [*Carpenter and Šulić,* 1988]. Earlier results from Eights, Antarctica, some published much earlier, were also used. Figure 6 shows a diagram indicating the equatorial regions beyond the plasmapause found to be penetrated by ducted whistlers during periods of moderate, relatively steady, geomagnetic agitation in the aftermath of weak to moderate geomagnetic storms. (Such magnetic conditions might prevail on ~4 to 12 days per month during years of other than the most disturbed or quiet solar conditions.) Detectable propagation was found to occur substantially less frequently beyond the plasmapause than within the nearby outer plasmasphere, but was nevertheless found to occur on at least one path on roughly one half of the days studied. Notable among the variations in occurrence indicated in Figure 6 are: (1) a minimum in activity in the 1800–2400 MLT sector, (2) a gap near dawn separating an outer belt of activity from a region of activity just outside the plasmapause, and (3) a radially broad region of relatively high activity in the afternoon sector.

The outer limits of propagation indicated in Figure 6, while quite approximate, are broadly similar to those indicated in Figure 4, which primarily represent propagation in the outer plasmasphere under conditions of extended recovery from disturbance. However, there is a difference in occurrence rate; as quieting occurs following a geomagnetic storm, the conditions of Figure 6 initially prevail. Then, as quiet conditions continue, the region beyond the plasmapause and within the outer limits of shading in Figure 6 tends to recover in density and hence to become the outer

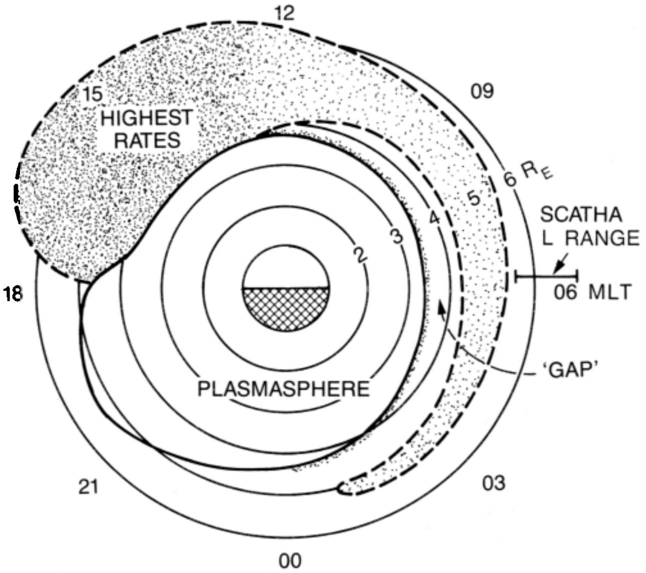

Fig. 6. Diagram indicating the equatorial regions beyond the plasmapause found to be penetrated by ducted whistlers during periods of moderate, relatively steady, geomagnetic agitation in the aftermath of weak to moderate geomagnetic storms (Kp = 6–7). The dot density provides a crude relative measure of the probability of event observation. The results are based upon recordings near the 75°W meridian in Antarctica. From *Carpenter and Šulić* [1987].

part of a larger plasmasphere. As the density increases, there is a transition from "trough-like" to "plasmasphere-like" propagation conditions, and the whistler rate tends to increase accordingly.

The structure in L and MLT of the activity in Figure 6 and the comparatively low rates in comparison to activity within the plasmasphere were discussed by *Carpenter and Sũlić* [1988] as being due to a combination of effects associated with lightning and with ionospheric and magnetospheric processes peculiar to the plasma trough region. For example, the observed dropoff beyond $L = 5.5$ near dawn in plasma trough propagation (and also in propagation during quieter conditions, as in Figure 4) may be in part due to limitations on high-latitude lightning source activity near 0600 MLT. Lightning location may also help to explain the small fraction of whistlers (say 1 in 10) that contain components propagating on paths outside the plasmapause, during many periods when such components are detected. Flashes causing whistlers propagating in the outer plasmasphere are more likely to be located equatorward than poleward of the typical plasmapause projection [e.g. *Orville and Henderson,* 1986], and on some occasions only the strongest or most poleward of these may be effective in exciting the plasma trough paths.

Ionospheric processes such as wave damping [e.g., *Sayasov and Ritz,* 1983], defocusing in the mid-latitude trough [e.g., *Storey and Malingre,* 1972], scattering by 10- to 100-m irregularities [e.g., *Bell et al.,* 1983], and focusing within 50 to 100-km electron density blobs [e.g., *Kelley et al.,* 1982] were suggested by *Carpenter and Sulić* [1988] to be causative of several features of the observed spatial distribution of whistler paths beyond the plasmapause, and also of the relatively low amplitude of the associated whistlers as compared to plasmasphere events. Magnetospheric processes may be important in causing the large difference in activity between afternoon and premidnight. Turbulent electric fields associated with substorms, including field-aligned potential gradients, may inhibit the formation of ducts beyond the plasmapause prior to midnight, while in the afternoon sector, ducts at the higher L values may tend to be relatively stable. This stability is attributed to the opposing effects of sunward convection and of the Earth's rotation, which cause the bulk velocities of the plasma in Sun-Earth coordinates to be comparatively low. The tendency for path radii to remain within ~5.5 R_E over much of the nightside may be associated with a transition at that distance from a dipole-like to a tail-like field line configuration. Continuous ducts may not form beyond the transition, due both to the dilated condition of the equatorial magnetic field and to the presence along the field lines of plasma sheet plasma, the spatial distribution of which should be insensitive to any low-altitude process by which ducts are otherwise generated.

5. DIRECTION FINDING ON WHISTLER MODE SIGNALS

An outstanding problem in VLF magnetospheric studies is the "imaging" of the distribution of whistler mode signals incident from above on the ionosphere. We report here briefly on the use of a tracking receiver/direction finder designed by Leavitt [*Leavitt,* 1975; *Leavitt et al.,* 1978]. This system was designed to provide essentially continuous azimuth of arrival information on signals propagating from ionospheric path endpoints to the receiver. Since an elevation angle is not determined, information from whistlers propagating on the paths of interest is used to determine path L values and hence to obtain coarse results on path endpoint range.

In a 1977 case study of arrival bearings of Siple transmitter signals at Roberval, Canada [*Carpenter,* 1980], several effects were observed, including (1) large (order of 180° shifts in arrival bearing, suggesting shifts in activity from one duct to another, (2) slow drifts in bearing, suggesting the effects of magnetospheric convection, and (3) quasi-sinusoidal fluctuations in bearing, suggesting some type of modulation of ionospheric propagation conditions near the path endpoint.

In a study of 1978 data from Palmer Station [*Carpenter and LaBelle,* 1982], it was found that whistlers associated with burst precipitation (Trimpi events) did not in general emerge from regions coincident with the affected great circle propagation paths, although they were centered within ~200 km of the affected paths. Temporal shifts in the arrival bearings were consistent with changes in the location of the perturbed ionospheric region, such that as the region approached a particular path, perturbations on that path began to be detected.

In a 1978 case study of multicomponent whistlers recorded simultaneously at Halley and at Siple [*Smith and Carpenter,* 1982], ionospheric exit points were estimated by crossed-bearing analysis from the two stations (a goniometer was used at Halley). Locations consistent with dispersion analysis (for L value) were obtained, and third-hop echoes were found to arrive from a direction consistent with their inferred path of third-hop propagation.

A remarkable application of several probing techniques occurred when *Tkalcevic* [1983] studied the apparent polarization of Siple transmitter signals and whistlers received at Palmer Station, Antarctica, located equatorward of Siple by ~1500 km. Three types of signals were received at Palmer and analyzed by a Leavitt direction finder. The direct subionospheric signal from Siple was found to be largely horizontally polarized, while both the Siple two-hop magnetospheric signal and whistlers that had propagated on its magnetospheric path exhibited essentially vertical polarization. Dispersion and arrival bearing analysis showed the magnetospheric signals to have exited the ionosphere near Siple; they therefore traveled ~1500 km in the Earth-ionosphere waveguide, after which their vertically polarized components could be expected to be dominant.

6. HOT PLASMA EFFECTS

Although whistlers are not readily used for the type of wave-particle interaction studies possible in Siple transmitting experiments (they provide a view of the magnetospheric impulse response, as opposed to its step response to an injected signal), features of the dynamic spectra of whistlers such as immediate or delayed triggering of emissions can be used to infer the occurrence of certain types of hot plasma processes. These features include noise suppression by whistlers and the so-called "third hop anomaly" of whistlers. Such effects are mentioned here only briefly, since wave-particle interactions are being discussed in other articles in this series in the contexts of Siple transmitter work and of wave-induced precipitation.

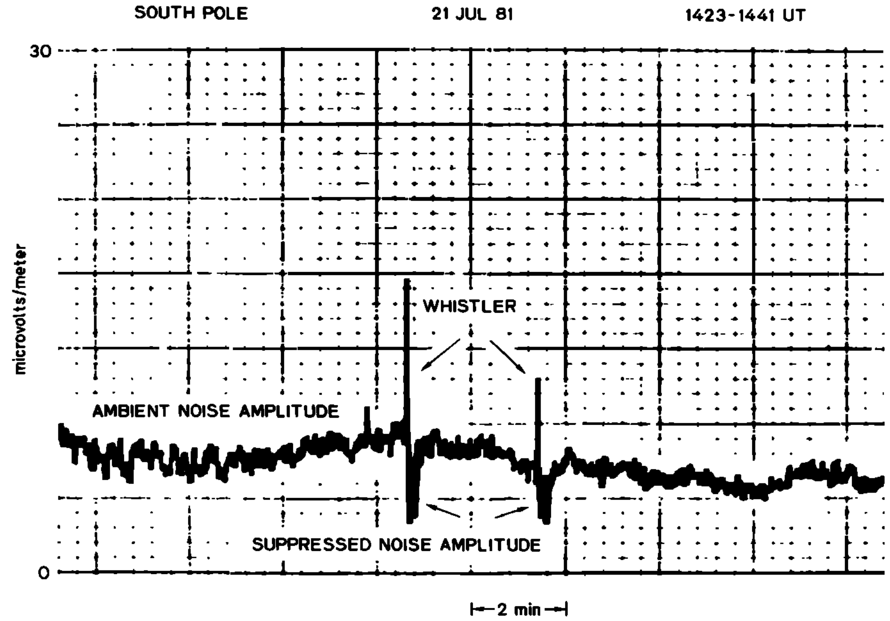

Fig. 7. Chart record from South Pole Station showing two cases of noise suppression by whistlers. Noise amplitude in the 1–2 kHz band is displayed versus time. From *Gail and Carpenter* [1984].

6.1. *Noise Suppression by Whistlers*

During some periods of whistler activity when a relatively steady background noise is also present on the whistler path(s), the background noise amplitude may decrease following the detection of a whistler, typically falling ~3-5 dB below preevent levels within ~5-10 s and recovering to preevent levels within ~15-30 s [*Gail and Carpenter*, 1984]. Such cases typically involve multihop echoing of the correlated whistler, partial suppression of the noise during the first pass of the whistler, and continuing suppression by the whistler echoes as the suppressed noise reaches a minimum amplitude and then recovers. Related perturbing effects have been noted by *Ho* [1973], who identified cases of triggering, modification, and attenuation of quasi-periodic VLF emissions (periods of 10-100 s) by whistlers.

Noise suppression by whistlers is relatively common, having been observed on ~5-10 % of the days at Siple and South Pole ($L \sim 10$) stations. Figure 7 shows a chart record from South Pole containing two suppression events. A possible inference in such cases is that the whistler has perturbed the particle distribution function along the path sufficiently to reduce the growth rate of the noise. However, another possibility is that the suppression is instantaneous in nature, and not mediated by a seconds-long diffusion process in velocity space. For example, in active experiments, *Helliwell and Katsufrakis* [1974] found that the suppression of the growth of a coherent signal by a disturbing whistler is virtually instantaneous (<50 ms). Further, *Helliwell et al.* [1986] found essentially no delay in the suppression of the growth of one coherent signal by another.

6.2. *The Third-Hop Whistler Anomaly*

An example of whistler wave growth, frequently appearing in combination with path coupling, is the third-hop anomaly, in which the third hop of an echoing magnetospheric whistler exceeds the first hop in intensity over some low range of frequencies [*Carpenter et al.*, 1986]. Case studies showed that this behavior can occur over periods ranging from tens of minutes to hours in duration. Most of the five cases studied in detail involved coupling of waves from one ducted magnetospheric path to another after the initial hop, as discussed above. The anomaly was interpreted as the result of df/dt dependent amplification of weak whistler signals by a gyroresonant wave-particle interaction, the amplification being facilitated by interpath coupling. Figure 3c illustrates the coupling process, wherein the reflected first-hop components from multiple paths contribute to the second-hop wave activity on an "active" path. The contributions from paths located close to the active path usually have $f-t$ curves that differ only slightly from the curve for the active path, with the result that the returning signal is smeared out in $f-t$ space and thus has a suddenly enlarged instantaneous bandwidth rather than the comparable or diminished one that would be expected (from increased dispersion) if no interduct coupling had occurred. This smearing effect is believed to inhibit further magnetospheric amplification of the waves by the "coherence bandwidth instability", which has been identified as the mechanism of temporal growth in Siple transmitter experiments [*Helliwell*, this issue]. On the other hand, the waves that couple to the active path from a path with relatively low travel time (usually one with a substantially lower endpoint latitude) may be separated from all others in f-t space sufficiently to preserve their discrete nature, and thus be capable of significant growth during the second and possibly subsequent hops of propagation.

7. PHASE MEASUREMENTS OF WHISTLER MODE SIGNALS

Most studies of the spectral characteristics of whistler mode signals have examined only the signal amplitudes as functions of frequency and time and have not considered the signal phases. There are two reasons for this, as *Paschal* *and Helliwell* [1984] have noted. First, naturally occurring signals such as whistlers and chorus are complex, and their phase characteristics are less easily interpreted than their amplitude characteristics. Second, phase is more difficult to measure than amplitude, requiring special recording techniques and analysis apparatus. Yet if the signals studied are simple enough (such as phase-coherent signals from VLF transmitters), their phases, which contain information independent of their amplitudes, can add a new dimension to our understanding of magnetospheric phenomena. This has been demonstrated by, for example, *Andrews et al.* [1978], who combined results from Doppler shift measurements on VLF transmitter signals with data on group delay to obtain simultaneous estimates for nighttime of the east-west component of magnetospheric electric field and of protonospheric coupling fluxes. Their findings were in general agreement with results obtained by other methods which separately probed the electric fields and fluxes.

A digital signal processing method has been developed and applied to analog tape recordings of Siple transmitter signals recorded at the conjugate station Roberval, Canada [*Paschal*, 1988; *Paschal and Helliwell*, 1984]. The program uses a constant frequency pilot tone recorded with the VLF data to correct tape speed errors and to reconstruct the signal phases. After the analog data are played back and digitized, the fast Fourier transfer algorithm is used to calculate the discrete Fourier transform of successive overlapping blocks of data. The resulting spectral points in each transform are convolved with a short window function to improve the shape of the synthesized filters, widening their passbands and suppressing sidelobe responses. Next, the phase of the pilot tone is measured and used to calculate the actual time of the particular data block. The advance in pilot phase from the previous block is measured and provides the instantaneous pilot frequency, and thus the speed error at that moment.

Once the speed error is known, interpolation between spectral points in the transform is used to generate a new spectrum whose points correspond to the original data frequencies. Finally, the phase of each spectral point in the speed-corrected spectrum is converted to a relative phase measurement by subtracting a phase of $2\pi ft$ radians, where f is the center frequency of the spectral filter and t is the time of the particular data block. These results are plotted, the transform of the next data block is taken, and so on. The resulting output for each spectral filter is a plot of the phase of the original VLF signal, filtered around the frequency f, with respect to the phase of a reference oscillator which has been running at exactly f Hz.

Applications of this method to Siple signals that exhibit evidence of temporal growth [*Paschal and Helliwell*, 1984] will be discussed in another article; here we discuss briefly the diagnostic uses of the method when fast temporal wave growth is not a dominant factor.

7.1. *Detection of Phase Changes Due to Duct Motion*

Figure 8 shows a spectrogram of a 2-s pulse at 3030 Hz from Siple as received at Roberval and described by *Paschal and Helliwell* [1984]. This pulse is typical of those that show little or no temporal growth during times of good propagation. The bar below the spectrogram indicates the duration of the transmitted pulse; the received pulse is slightly longer, about 2.1 s, due to multipath propagation.

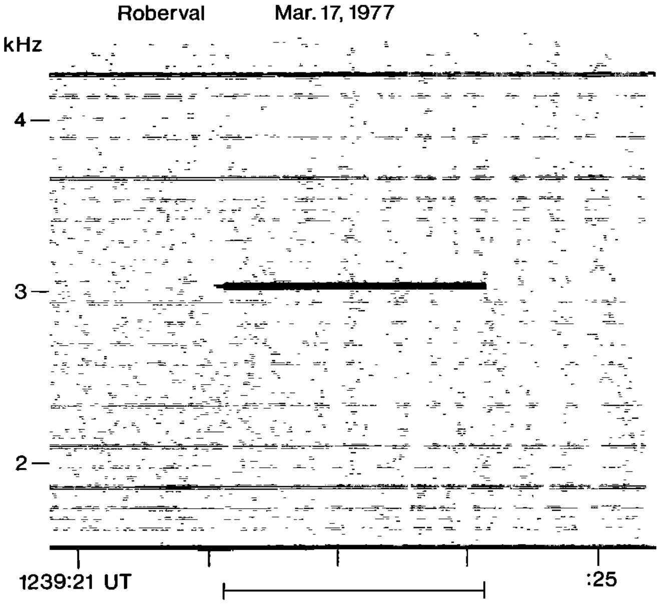

Fig. 8. Spectrogram of a 2-s pulse transmitted from Siple, Antarctica, to Roberval, Canada, at 3030 Hz. The pulse is constant in amplitude, showing neither temporal growth nor emission triggering. The lines in the backround represent interference from the local power grid at multiples of 60 Hz. The spectrogram was produced following digital processing of an analog recording. From *Paschal and Helliwell* [1984].

Figure 9 shows the result of analyzing a series of 2-s pulses from the same period [*Paschal*, 1988]. The pulses were transmitted at 10-s intervals at 3030 Hz as part of a program combining frequency ramps and fixed frequency signals. The upper panels show the log magnitude of the pulse, while the lower panels show the phase of the received signal with respect to a synthesized oscillator running at exactly 3030 Hz. The magnitude plots show a slow rise in amplitude during the first 0.1 s, before the main part of the pulse, with plateaus that appear to be the effects of additional paths of propagation. The phase plots show a Doppler shift that varied from -0.10 Hz to -0.20 Hz during the ~30-s period displayed. Doppler shifts of this magnitude have been observed on whistler mode signals from VLF communication transmitters by, for example, *McNeill* [1967]. Considering the effects on phase path of duct drift and plasma flux, and using an analysis similar in concept to analyses performed previously by *Thomson* [1976] and *Andrews* [1980], *Paschal* [1988] concluded that the predominant effect involved was an outward duct drift. Outward drifts are commonly observed at this postdawn (~0730 MLT) local time on magnetically quiet days [*Carpenter and Seely*, 1976; *Carpenter*, 1978].

7.2. *Correlation of Phase Changes With Magnetic Micropulsations*

The variations in Doppler shift within the 30-s period displayed in Figure 9 suggest the presence of a fluctuating component comparable in amplitude to the average value. Thus it is possible that the high-altitude portion of the

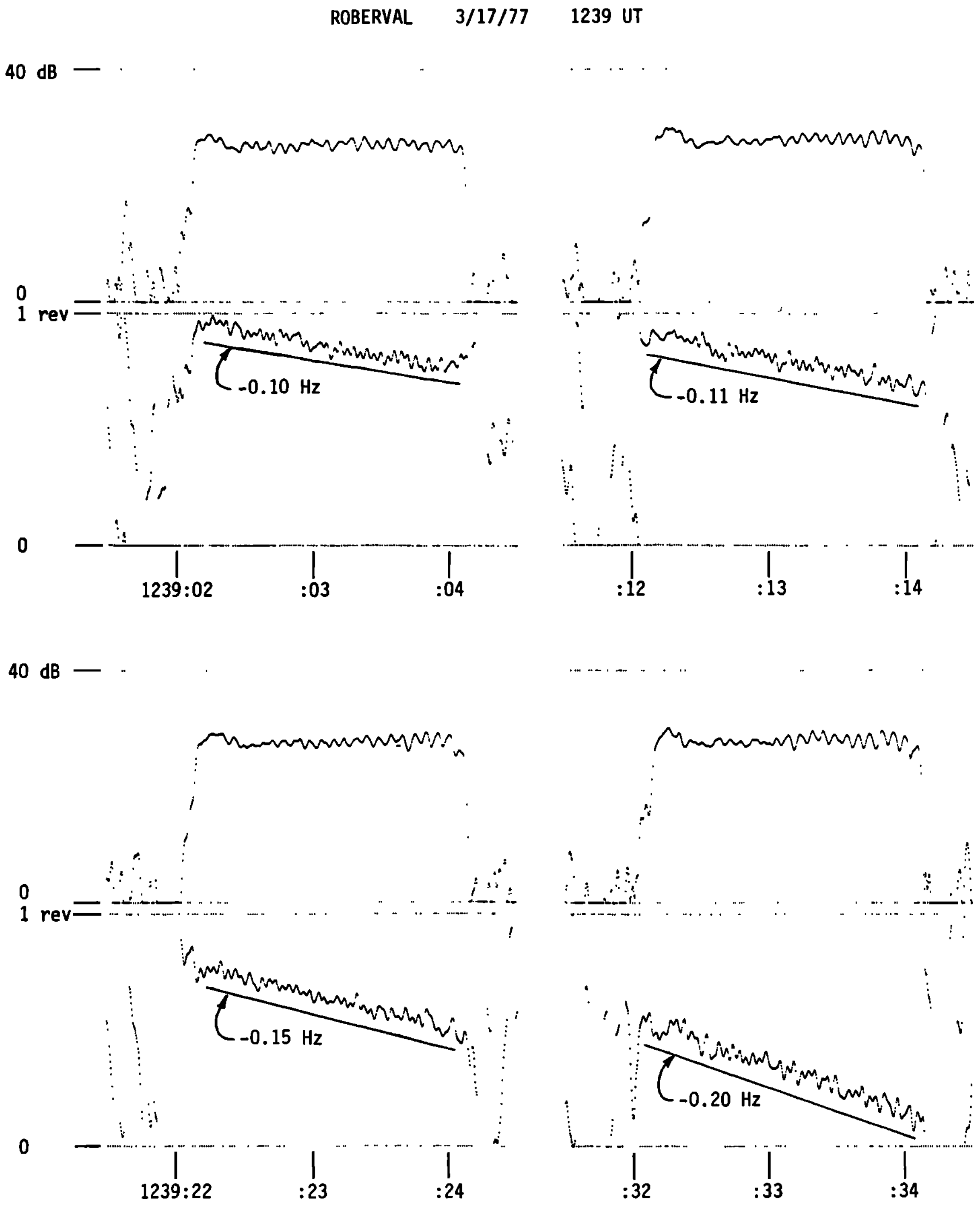

Fig. 9. Magnitude and phase plots of a series of 2-s pulses at 3030 Hz from the Siple transmitter, received at Roberval, Canada. The digital processing method described by *Paschal and Helliwell* [1984] was used. The upper panels show log magnitude of the pulse within a 20-Hz bandwidth, and the lower panels the phase with respect to a synthesized oscillator running at exactly 3030 Hz. The pulses show a Doppler shift ranging from –0.10 to –0.20 Hz. From *Paschal* [1988].

whistler mode duct was undergoing cross-L motions associated with magnetic pulsations, as discussed previously by *Andrews* [1977] and by *Rietveld et al.* [1978].

Much more complete evidence of pulsations in phase path length was provided by an 11-min continuous recording of a special two-tone Siple transmitter format that was originally intended to simulate line radiation in the magnetosphere. The bottom panel of Figure 10 shows the phase of an equivalent VLF signal at 3965 Hz, after initial processing of two separate signals at 3950 and 3980 Hz and high-pass filtering. The upper panels show filtered magnetic field H and D components recorded by a magnetometer at La Tuque, in the near vicinity of the VLF receiver (courtesy of L. Lanzerotti and C. Maclennan).

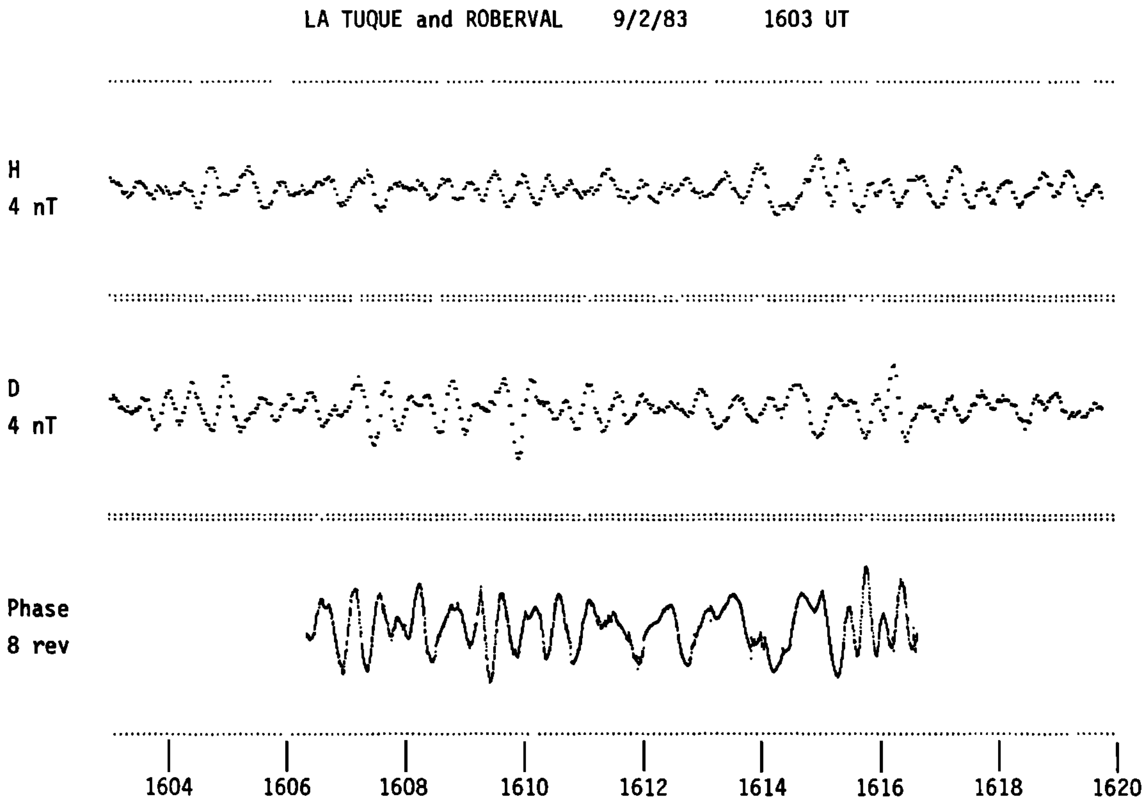

Fig. 10. Comparison of high-pass-filtered magnetometer and VLF phase data, from a period of Siple transmissions of two signals at 3950 and 3980 Hz. The upper panels show *H* and *D* component data from the Bell Laboratories magnetometer at La Tuque, Canada, in the vicinity of the VLF receiver (courtesy of L. Lanzerotti and C. Maclennan). The bottom panel shows the phase of an equivalent VLF signal at 3965 Hz, after digital processing of the 3950- and 3980-Hz signals. From *Paschal* [1988].

The presence of a correlation between the VLF and ULF, particularly between VLF and the *D* component, is strongly suggested by the compared spectrograms of Figure 11. The spectral features are not persistent in time, suggesting an irregular, driven process. VLF features appear to lead the corresponding features in *D* by 20–30 s, which would be consistent with a process that modulates the VLF path at high altitudes and is then observed at ionospheric heights following propagation at the Alfven speed along the field lines.

This case has been further interpreted by *Paschal* [1988] in the light of the earlier work by *Andrews* [1977] and *Rietveld et al.* [1978]. Our purpose here is mainly to draw attention to the potential of this type of measurement. It is apparently sensitive to an equatorial component of the field line perturbation, and thus provides information complementary to the low-altitude data obtained by the surface magnetometer. Furthermore, in conjunction with application of dispersion techniques, the *L* shell of propagation can be found. If used during transmissions of other signals that experience fast temporal growth, the technique might permit study of the modulation of VLF wave growth at ULF frequencies with periods of ~10 s and longer. Siple signal receptions occur under both day and nighttime conditions [*Carpenter and Bao*, 1983], making possible study of a variety of pulsation phenomena.

As part of an active experiment, the method would necessarily be applied selectively, for example, at times when particular types of magnetic pulsation activity are observed. The method would also require use of the transmitter in such a way as to avoid fast temporal growth (the phase changes associated with such growth would obscure the much smaller effects due to pulsations in phase path). This is becoming increasingly feasible; because of the apparent dependence of magnetospheric wave amplification on input wave coherence, two-frequency transmissions with frequency separations of 20–30 Hz have been found to be an effective means of suppressing temporal wave growth while at the same time achieving a detectable signal at the conjugate ground receiver [*Helliwell et al.*, 1986].

8. CONCLUDING REMARKS

8.1. *Summary*

In the beginning the past decade, the whistler method of measuring equatorial electron density was found to agree with in situ satellite electron density measurements by a radio technique. Furthermore, the whistler method of measuring the east-west component of the convection electric field in the outer plasmasphere was found to agree, under conditions of mapping in a dipole magnetic field, with simultaneous results from incoherent scatter radar. A global model of the east-west convection electric field in the outer plasmasphere during substorms was developed and has since been useful in the interpretation of satellite observations of

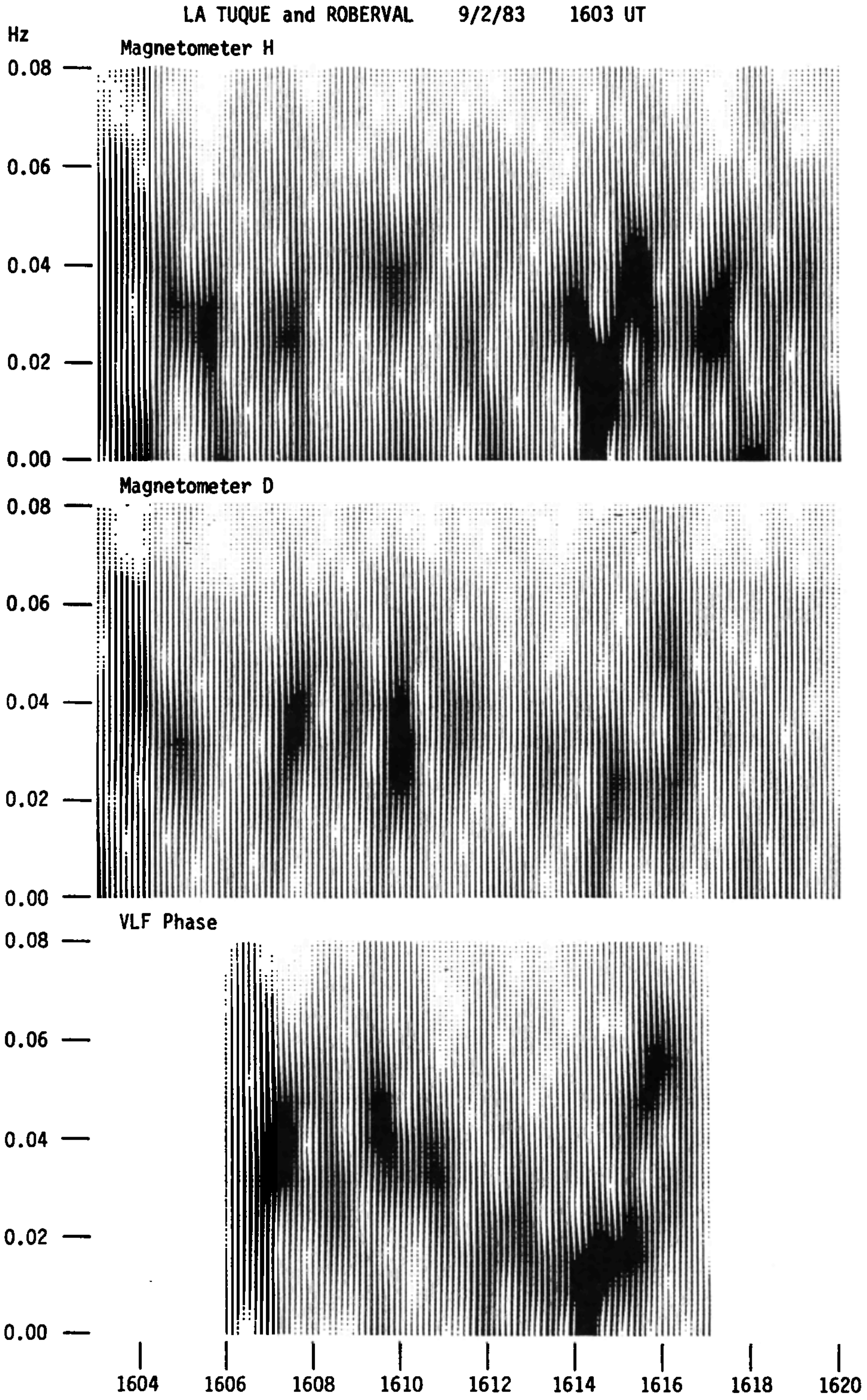

Fig. 11. Spectrograms of the filtered magnetometer and VLF phase data displayed in Figure 10. Similar features appear in all three plots. The VLF features between 1606 and 1612 appear to lead corresponding features in the *D* component by 20–30 s. From *Paschal* [1988].

low-energy ions injected into the plasmasphere during substorms.

The detection of whistlers and their use for magnetospheric diagnostics have been important elements in recent studies of burst precipitation into the ionosphere induced by whistlers and by other transient whistler mode waves propagating in the magnetosphere. Whistlers have also been used to obtain data on the *L* values and equatorial electron densities associated with the propagation paths of signals from the Siple VLF transmitter.

The process of untrapping of downcoming wave energy from ducts in the upper ionosphere and the upward repropagation of portions of the energy following reflection in the lower ionosphere lead to the excitation of adjacent ducts as well as to upward propagation in the nonducted mode. Efficient interduct coupling has been found to occur over north-south ionospheric distances of >1000 km.

Studies of the outer limits of observed ducting revealed dayside path radii in the 6 to 8-R_E range and nightside limits of ~5.5 R_E. These approximate limits were observed during both quiet periods and periods of moderate but relatively steady magnetic activity in the aftermath of weak to moderate geomagnetic storms. Ducted propagation beyond the plasmapause was found to occur regularly in the 0000-1800 MLT time range, but with variable rates and at various locations with respect to the plasmapause position. The special features of this propagation are believed to be related to conditions of lightning excitation, ionospheric penetration, and wave-particle interactions that are special to the region beyond the plasmasphere.

A tracking receiver/direction finder employed at Palmer Station and at Roberval, Canada, conjugate to Siple, was successfully used in studies of Siple transmitter path endpoints, whistlers associated with particle precipitation, and the polarization of Siple transmitter signals received at Palmer both directly and after magnetospheric propagation. Consistent results were obtained when comparisons were made with goniometer data from Halley Station and path L value data from whistler dispersion analysis.

Evidence that whistlers can depend strongly upon magnetospheric amplification was found in suppression of background noise by whistlers and in the third-hop anomaly, in which the third hop of an echoing whistler exceeds the first hop in intensity over some low range of frequencies.

New aspects of Siple wave injection experiments were demonstrated by the application of a new phase measurement method to Siple signals that did not exhibit fast temporal growth during passage through the magnetosphere. This method, a refinement of techniques developed previously by New Zealand workers, is capable of detecting fluctuations in phase path with period of ~10 s and greater, and thus can be used to study magnetospheric convection and coupling fluxes along field lines of propagation as well as pulsations associated with ultralow-frequency perturbations of the geomagnetic field.

8.2. *Future Directions*

Whistler mode probing of the magnetosphere is capable of many further refinements and offers many as yet unrealized research opportunities. A problem area of great future interest is the dependence of the response to wave injection, in terms of both nonducted and ducted magnetospheric propagation, on the observed properties of source lightning. The physics of ducts and of ducting remain an outstanding problem area for experiment and theory. There is much more to learn about the interplay of factors such as particle precipitation, which may cause attenuation and scattering of whistler mode waves, and those aspects of wave-particle interactions that enhance wave growth. Whistler probing in support of wave-induced precipitation studies and wave injection experiments will certainly continue and probably will be extended in scope.

The basic whistler method of probing magnetospheric thermal plasma structure and dynamics has been applied quite sparingly in recent years, in spite of its great potential. It is possible that more of this potential can be realized in future years if automatic processing techniques involving event recognition, direction finding, and dispersion analysis can be extended to the complex data observed at middle and high invariant latitudes. Eventually, wave injection techniques should be developed to provide for controlled whistler mode sounding of the magnetosphere, by analogy to the sounding methods that have been applied with success to the regular ionosphere. A major contribution to such development would be further use of whistler mode phase path measurements to study bulk plasma cross-L flow, ionosphere-magnetosphere coupling fluxes, and ULF perturbations of the geomagnetic field.

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