Ducted Magnetospheric Propagation of Signals From the Siple, Antarctica, VLF Transmitter

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A study has been made of the conditions under which ≃2- to 6-kHz VLF signals transmitted from Siple, Antarctica ($L \simeq 4$), are observed at the conjugate ground station Roberval, Canada, following ducted propagation through the magnetosphere. In 1973 and 1974, signals detected from visual inspection of spectrographic records were present on roughly 20% of the days, typically for ≃4 of 8 observing hours. As had been expected, the observations appeared sensitive to conditions of whistler propagation and of wave growth in the magnetosphere. Signal observations were most frequent during quieting following magnetic disturbance. A diurnal activity peak was found at dawn, and day side activity levels were generally higher than those at night. Signal travel times were compared to the dispersion properties of whistlers recorded at Siple and Roberval during July–August 1973 and September–November 1974. The signal path equatorial radii were found to be concentrated in the range 3.5–4.5 R_E, which is centered roughly on the Siple/Roberval field lines. At ionospheric heights this range corresponds to a latitude interval of ≃3°. Multipath propagation was frequently observed, but a single path was usually prominent in terms of received amplitude. During relatively quiet conditions the paths were located within the outer plasmasphere; during moderate disturbance they frequently appeared in the region of steep plasmapause density gradients.

INTRODUCTION

Whistler mode signals from VLF transmitters have been used for a number of years in ground-based studies of magnetospheric wave propagation and wave-particle interaction phenomena. Much of this work has concerned signals propagating at L = 2–3 from ≃0.1- to 1-MW sources operating in the 15- to 20-kHz range [e.g., *Helliwell,* 1965; *Allcock and McNeill,* 1966; *McNeill and Andrews,* 1975; *Kiselev et al.,* 1975]. Signals propagating near L = 3.6 from the low-power ≃100- to 1000-W Omega stations at ≃10–14 kHz have also been studied [e.g., *Kimura,* 1968; *Carpenter,* 1968*a*].

Recently, a new capability for probing the outer plasmasphere has been attained through the establishment of special low-power (≃1–2000 W) experimental VLF transmitting facilities near L = 4 at Siple, Antarctica [*Helliwell and Katsufrakis,* 1974], and on a campaign basis in Alaska near L = 3 [*McPherson et al.,* 1974] and near L = 4 [*Koons and Dazey,* 1974].

The Siple (Antarctica)/Roberval (Canada) transmitting experiment has revealed remarkable new features of wave-particle interactions in the magnetosphere, including exponential growth to a saturation level, interaction of signals with radiation from power distribution systems, and suppression of natural noise in frequency bands adjacent to a transmitter frequency [*Helliwell and Katsufrakis,* 1974; *Stiles and Helliwell,* 1975; *Helliwell et al.,* 1975]. It is desired to know more about the circumstances under which these phenomena occur and in general to investigate whistler mode propagation between hemispheres near the plasmapause. A preliminary study of Siple signal observations has therefore been done, with some emphasis on finding the positions in space of the signal propagation paths. This research note presents the results of this study.

The new experiments extend our knowledge in several ways. Near L = 2.5 the observed properties of ≃15- to 20-kHz signals following magnetospheric paths to ground points appear to depend heavily on propagation conditions. In particular there are night side maxima in activity [e.g., *Helliwell,* 1965; *McNeill and Andrews,* 1975; *Kiselev et al.,* 1975] and peaks in activity along field lines conjugate to the transmitter and to receivers [*Allcock and McNeill,* 1966]. The occurrence data change somewhat when attention is focused on triggering of VLF emissions by signals from the high-powered transmitters and on propagation of signals from the lower-power Omegas; there are high levels of such activity near dawn and a measure of gyrofrequency control such that preferred field lines of propagation may be slightly nonconjugate with respect to the transmitter [*Kimura,* 1968; *Carpenter,* 1968*a*]. Further changes appear near L = 4 in the Siple signal data; there are relatively high day side levels of activity, and while the preferred magnetospheric paths are on the average close to the Siple/Roberval field lines (partly as the result of deliberate choice of station locations and transmitter frequencies), within the latitude range of observations there is clear evidence of gyrofrequency control.

Variations with L are observed in the conditions of artificial triggering of noise. Such triggering at 15–20 kHz near L = 3 by high-power sources usually occurs in the absence of observed triggering of emissions by whistlers or of propagation of natural emissions along the same magnetospheric paths. However, triggering by the low-power Omegas near L = 3.5 is frequently accompanied by such natural activity, and triggering by the Siple signals near L = 4.0 regularly occurs in the presence of whistler triggering and complex VLF emissions.

DESCRIPTION OF THE EXPERIMENT

Siple, Antarctica, site of the transmitter and its associated 21-km dipole antenna, is at 76°S, 84°W, and $L \simeq 4$. The conjugate station Roberval, Quebec, is at 49°N and 72°W. Beginning in late April of 1973 and throughout much of 1973 and 1974, the transmitter operated during periods of approximately 8 hours per day on 5–6 days per week. Figure 1, upper panel, shows an example of a transmitted format. In this case, frequency ramps were mixed with 1-s pulses at stepped frequencies.

The transmitting system is relatively narrow band and usually operates within a tunable 1-kHz range. For typical operation near 5 kHz, radiated power is of the order of 1 kW for an antenna input of 30 kW [*Raghuram et al.,* 1974]. Below ≃3

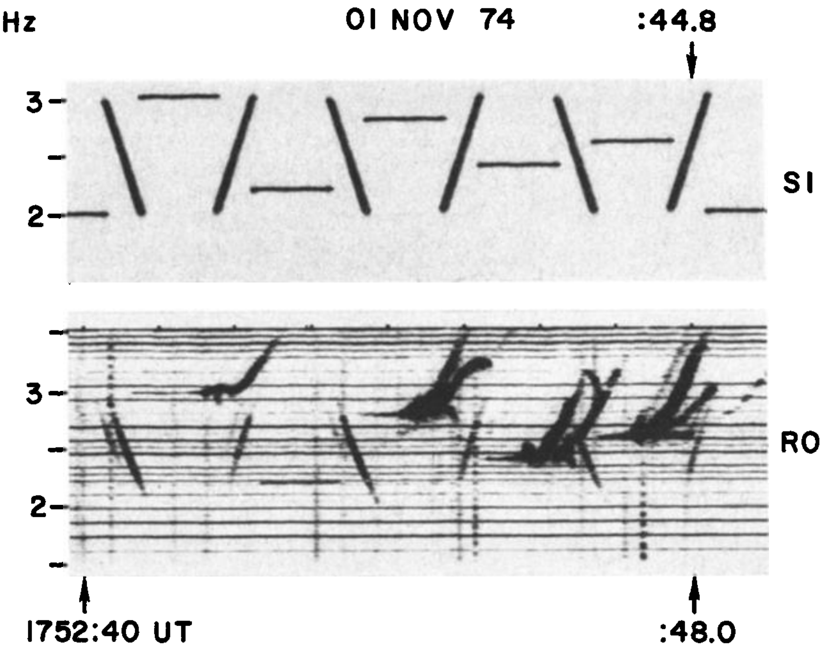

Fig. 1. Frequency-time records from Siple (top) and Roberval showing the format transmitted (top) and the signals received about 3.2 s later at Roberval (bottom). The Siple record has been advanced 3.2 s in time for purposes of comparison. The long horizontal lines on the Roberval record are due to currents in the local power distribution system.

kHz, antenna input power is reduced by transmitter tuning limitations. At these lower frequencies, antenna efficiency is also reduced; radiated power near 2 kHz is estimated to be ≃100 W for an antenna input of ≃10 kW. Because of the manner in which the transmitted wave form is synthesized, maximum power into the antenna for a given transmitter tuning is usually achieved at the upper limit of the operating frequency band (for further system details see E. Paschal (unpublished manuscript, 1974)).

Broad band VLF recordings were made at Roberval throughout scheduled transmitter operations and at Siple during scheduled interruptions of the transmissions for 1 min either every 5 or every 15 min and during hourly or half-hourly ≃10-min intervals used for discretionary changes in transmitter frequency. The Roberval recordings were initially scanned for transmitter signal activity by a combination of aural monitoring and visual analysis of the output of a real time spectrum analyzer. Properties of the transmitter signals identified in this way were then determined by analysis of spectrographic films.

Figures 1 and 2 show how a radial coordinate of a field-aligned signal path is determined. In Figure 1, frequency-time records show the Siple transmitter format (top) and the spectra observed at Roberval (bottom) during a ≃10-s interval on November 1, 1974. The horizontal lines on the Roberval record are induced by currents in the local power distribution system. For purposes of comparison, the Siple record has been moved forward 3.2 s in time to account approximately for the time of propagation of the signals between hemispheres along field-aligned paths. (Time at the two stations is determined from identical time code generators operated from station frequency standards. Timing is subject to daily corrections by means of WWV transmissions or their equivalent; relative time between Roberval and Siple is known to within ≃±5 ms.)

In the path analysis, travel time τ_{tr} of Siple signals at one or more fixed frequencies f_{tr} or at various ramp frequencies is measured, usually to an accuracy of <±2%. In most cases the Siple signals appear to follow the path of an observed whistler component; an observed pair τ_{tr}, f_{tr} corresponds within experimental error to a point on the frequency-time curve of the whistler, as illustrated in Figure 2*a* (see *Carpenter* [1968*a*] for application of this method to a case of 10.2-kHz Omega signals from Forest Port, New York). From the observed nose frequency of the whistler, labeled $f_n(2)$, a latitudinal or magnetic shell coordinate of the path can be determined with the aid of calculations relating nose frequency to path equatorial gyrofrequency (see *Park* [1972] for an example of such calculations).

Figures 2*b* and 2*c* show in a simplified way how the method applies to cases of multipath whistler activity. In Figure 2*b* there are three whistler components, labeled 1, 2, and 3. From dispersion analysis these are found to follow paths in the outer plasmasphere with equatorial radii of ≃3.7, 4.3, and 4.6 R_E, respectively. The Siple signal is readily associated with the path of component 2. Figure 2*c* shows a more complicated situation in which a fourth whistler component is present and the transmitter frequency is lower. With allowance for experimental error it is possible to associate the observed values of τ_{tr}, f_{tr} with either component 2, propagating to ≃4.3 R_E in the outer plasmasphere, or with component 4, propagating to ≃4.6 R_E in the region of steep plasmapause density gradients. Such an ambiguity may often be resolved by study of additional features of the records. Whistlers originating in the northern hemisphere and propagating to Siple are most convenient for the analysis because of their high rate of occurrence and excellent definition. However, two-hop echoes of these whistlers at Roberval are also useful, since the component corresponding to Siple signal propagation is often a prominent feature, and occasionally the only feature, of the two-hop activity.

The availability of whistler data for dispersion analysis depends upon both the natural activity and the passive recording schedule at Siple. In June–August, Siple whistler rates are

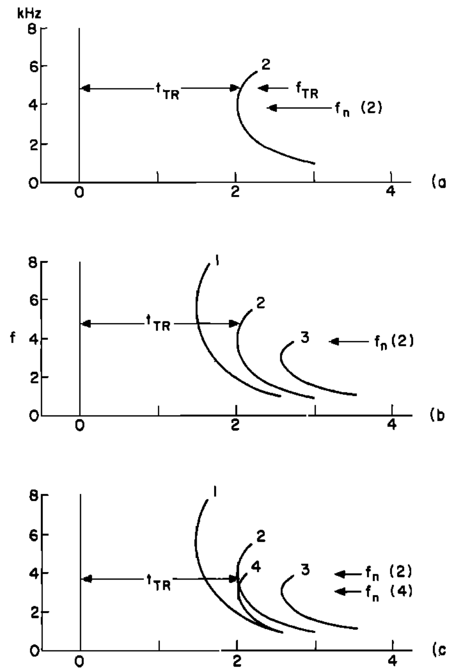

Fig. 2. Diagrams showing the use of whistlers to determine the equatorial radius of the field-aligned path followed by Siple signals. (*a*) Case of propagation of Siple signals on the path followed by a whistler, showing the relation of the whistler dispersion curve to the measured travel time of the transmitter signal τ_{tr} at frequency f_{tr}. (*b*) Case of propagation of Siple signals on one of three whistler paths in the outer plasmasphere, showing the relation of the whistler component propagating on that path to the observed values of τ_{tr} and f_{tr}. (*c*) Case of possible propagation of Siple signals on two whistler paths; one (path of component 2) is in the outer plasmasphere, and the other (path of component 4) is in the region of steep plasmapause gradients. Additional information is needed in order to resolve the ambiguity.

high ($\simeq$1–10 per minute), and the signal path analysis is limited primarily by the ability to measure the signal travel time to Roberval. In September–October the whistler activity at Siple is generally below June–August levels, and the path analysis may on occasion be limited by insufficient duration of passive recordings.

The transmitting experiment is in a constant state of engineering and scientific development. For example, in 1973 and early 1974, signal frequencies were prescheduled, while since mid-1974 the Siple operators have used a real time broad band video display of the spectrum of whistler and natural VLF noise activity as a guide to discretionary adjustments in transmitter frequency. Earlier observations at Eights, Antarctica, of natural whistlers and signals from northern hemisphere VLF transmitters [*Carpenter,* 1968*a*] suggested that the transmitter frequency should be set near the upper cutoff frequency of a well-defined whistler component, as indicated in Figure 2*a*. This strategy, based on the reported evidence of a maximum in observed whistler intensity near the upper cutoff, has been implemented with success.

Operating schedules are necessarily limited by considerations of manpower and of other responsibilities and activities at the station. In the austral winter, schedules have emphasized the dawn sector hours of expected high levels of wave growth activity, while near the austral summer, considerations of outside work in daylight have dictated a shift to day side transmissions. The limitation of daily schedules to $\simeq$8 hours in duration is dictated in part by the need for regular involvement of an operator in monitoring the natural VLF background and in occasional retuning of the system. Retuning presently requires a period of the order of 5 min.

Signal formats have varied widely. For example, in July and August 1973 the formats emphasized FSK with variable pulse length as part of a study of wave growth, and pulsed CW as part of a balloon X ray campaign. A 'universal' program, designed to explore a wide range of effects, was in frequent use during September–November 1974 (a part of this program is illustrated in Figure 1). In spite of its developmental, exploratory nature, system operation has been remarkably regular, and good recording coverage has been achieved at Roberval.

In the present study, certain aspects of Siple signal detection during all of 1973 and 1974 were surveyed, and detailed path analyses were performed on data from the 5 months July–August 1973 and September–November 1974. The latter data set will be called the 5-month data base, or FMDB. For statistical purposes, observing time at Roberval was divided into UT hours. Siple signals of whatever intensity, duration, and time distribution, observed within a single UT hour, were considered a single event.

EXPERIMENTAL RESULTS

Signals were detected during 1 or more hours on approximately 20% of the days of transmitting activity in 1973 and 1974. Table 1 shows the occurrence data for several periods, including July–August 1973 and September–November 1974 (the FMDB), when the percentage of reception days was relatively large, near 30%. In the FMDB the average duration of a day's transmitter operation was 7.75 hours. On days of signal detection at Roberval the average time coverage of signals was 3.82 hours.

A histogram of the occurrence in 1973 and 1974 of transmitted and observed signals as a function of universal time (bottom) and magnetic local time (top) is shown in Figure 3. The ratio of observations to transmissions, N_{obs}/N_{tr}, is shown below. Typical values are near 0.10, less than the 0.20 noted above because of the factor of $\simeq$2 difference in duration between typical transmission and detection intervals.

The values of N_{obs}/N_{tr} are relatively low between 0500 and 1000 UT. Near 1000 UT (0500 MLT) there is a factor of $\simeq$2 increase to a broad peak centered at about 1200 UT, followed by a decreasing trend across the day side. Near 2000 UT (1500 MLT) there is a factor of $\simeq$2 drop to a level below that observed in the 0500–1000 UT period. Between 0000 and 0500 UT there were relatively few transmissions and no cases of detection at Roberval. That the general features of the lower histogram are statistically significant is suggested by the lack of large variation near 1400–1500 UT, when both the number of transmissions and the number of receptions decreased sharply (this was an artifact of scheduling arrangements).

TABLE 1. Siple Signal Transmission and Detection Activity

Period	Transmission Activity, no. of days	Detection at Roberval, Canada, no. of days	Detections/ Transmissions × 100, %
1973	148	35	24
1974	226	37	16
1973–1974	374	72	19
July–Aug. 1973	54	18	33
Sept.–Nov. 1974	53	16	30

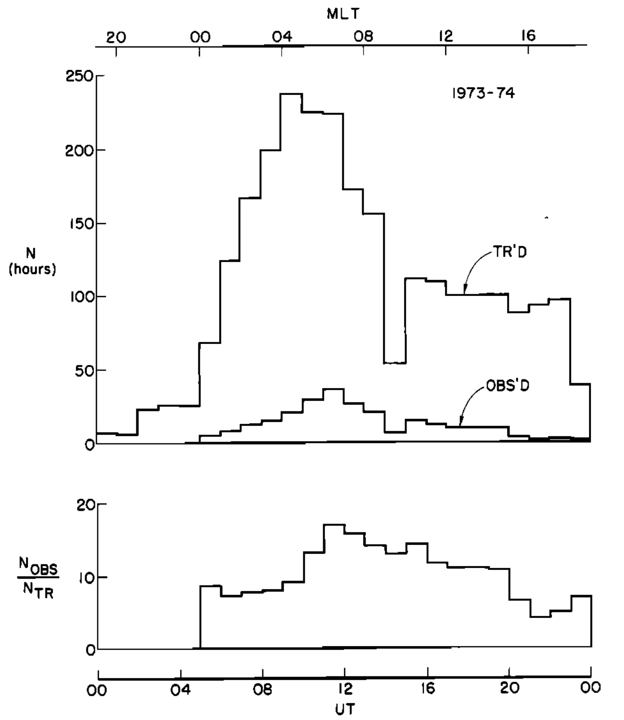

Fig. 3. Histogram for 1973 and 1974 of transmitter operations at Siple and of signal detection at the conjugate Roberval station as a function of time (top, magnetic local time; bottom, universal time). For statistical purposes all transmissions or detections within a given UT hour are considered to be a single event.

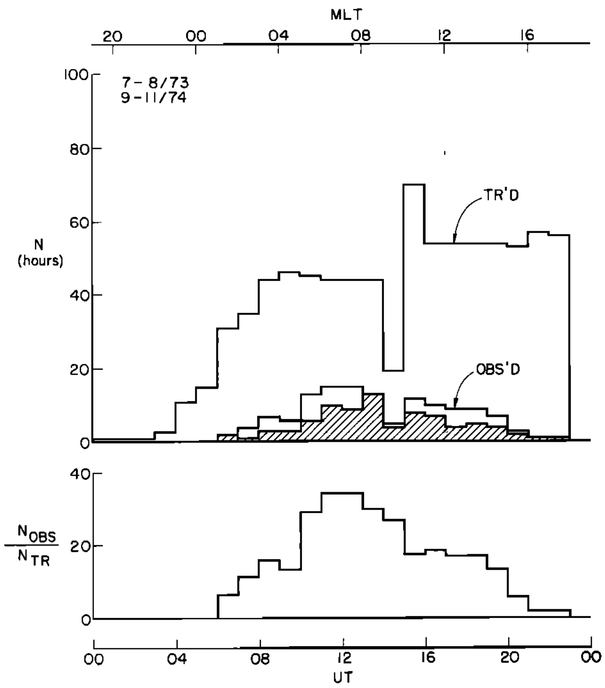

Fig. 4. Histogram similar to that of Figure 3 but for the FMDB indicated. The shaded area represents the ≃60% of the hours of detection for which a path analysis could be performed.

Figure 4 shows a histogram like that of Figure 3 but for the 5-month data base (FMDB). The hatched area indicates the ≃60% of the hours of detection for which path analyses could be performed. The lower histogram, showing the detection/transmission ratio, agrees in general form with the graph for all of 1973 and 1974 in Figure 3. The broad peak centered at ≃1200 UT (0700 MLT), with onset near 1000 UT (0500 MLT), is well defined, as is the sharp drop in day side activity near 2000 UT (1500 MLT). Again the ratio is insensitive to the drop in transmitter activity at 1400–1500 UT.

The relation of transmitter signal detection to worldwide average magnetic activity is illustrated in Figure 5. Two sets of data were used: all cases of detection in 1974 (solid circles) and the eight most intense cases of signal activity in 1974 (open circles). Values of $\sum Kp$ were recorded for each UT day of signal detection and for the four preceding and following days. For the two data sets, the median value of $\sum Kp$ was found for each day in the 9-day sequence. The results show a strong preference for conditions of quieting. The day of observation is on the average preceded by a gradual quieting trend, characteristic of the aftermath of weak to moderate magnetic storms. The days of exceptional activity (open circles) tend to occur under conditions quieter than those representing the larger data set.

The rapid rise of the median $\sum Kp$ following the day of detection reflects the relatively fast rise time of magnetic storm activity and the tendency for relatively deep quieting to be of limited duration.

Histograms relating transmission activity to transmitter frequency are shown in Figure 6. The data are from the FMDB; the format is similar to that of Figure 4. Approximately 75% of the transmissions were in the range 3.5–6.0 kHz. The lower histogram shows relatively frequent detection near 3 kHz. The dip in values of N_{obs}/N_{tr} near 4 kHz is not presently understood; more data are needed in order to evaluate details of this kind.

A histogram of signal detection as a function of path equatorial radius is shown in Figure 7. The data represent 81 hours of observation, the shaded portion of the FMDB shown in Figures 4 and 6. The path equatorial radius was estimated from whistler diagnostics developed by N. Seely (personal communication, 1975) using a hybrid magnetic field model that combines an IGRF (international geomagnetic reference field) internal field [*Mead,* 1970] with the *Olson and Pfitzer* [1974] symmetric model. Roughly 80% of the observations fall in the range $3.5 < R/R_E < 4.5$.

The dashes in Figure 7 show the predicted form (not the absolute values) of the histogram under the single assumption of a propagation cutoff on paths on which the transmitter

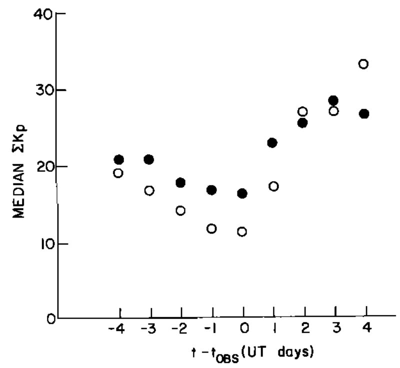

Fig. 5. Relation of Siple transmitter signal detection at Roberval to worldwide average magnetic activity. The time scale represents UT days referred to the day of signal detection. Each data point represents a median of the $\sum Kp$ values for that day. Solid circles represent all cases of signal detection in 1974; open circles the eight most active cases in 1974.

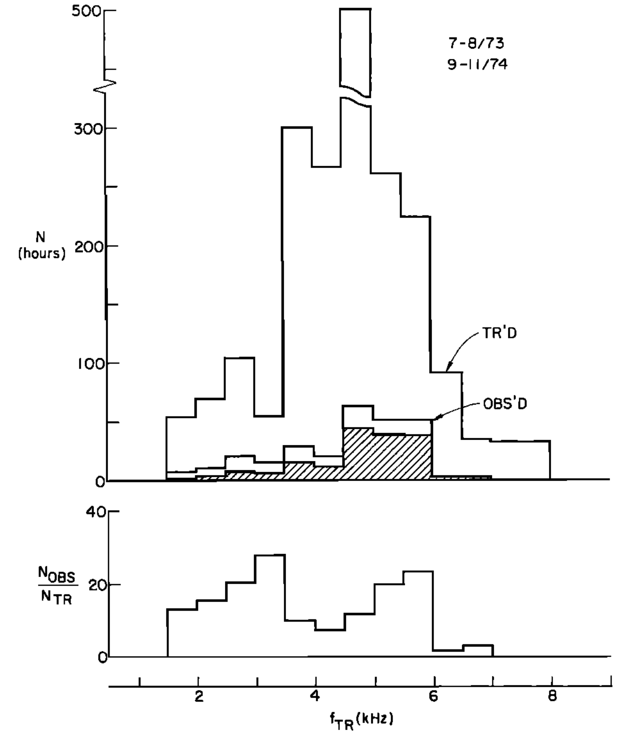

Fig. 6. Histogram for the FMDB showing Siple transmitter operations and signal detection at Roberval as a function of transmitter frequency. The shaded area represents the $\simeq$60% of the hours of signal detection for which a path analysis could be performed.

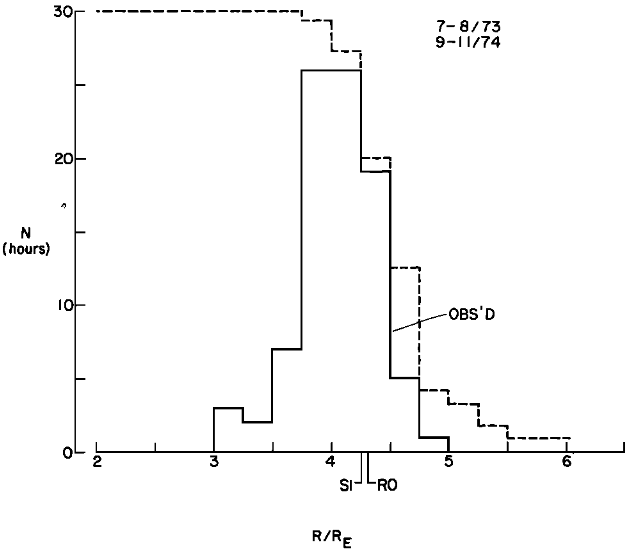

Fig. 7. Histogram for the FMDB showing cases of Siple signal detection at Roberval (solid lines) versus inferred equatorial radius of the field-aligned signal paths. The equatorial radii corresponding to the field lines reaching Siple and Roberval at ground level at noon MLT are shown on the horizontal axis. The dashed curve shows the predicted form of the histogram under the single assumption of a propagation cutoff on paths on which the transmitter frequency is above half the equatorial electron gyrofrequency (i.e., the condition for untrapping of waves in field-aligned ducts of enhanced ionization).

frequency is above half the equatorial electron gyrofrequency. On such paths, frequencies above $f_{Heq}/2$ are expected to become unducted [e.g., *Smith,* 1961; *Angerami,* 1970] and thus undetected on the ground. The radii corresponding to the field lines passing through Siple and Roberval at local noon are indicated below. (In the hybrid geomagnetic model used, the field line passing through Siple at ground level reaches $R = 4.30\ R_E$ at 0000 MLT and $R = 4.25\ R_E$ at 1200 MLT. For Roberval the values are $R = 4.37\ R_E$ at 0000 MLT and $R = 4.32\ R_E$ at 1200 MLT.)

Figure 8 shows the information of Figure 7 projected down the field lines onto the earth's surface (using the hybrid geomagnetic model) and organized according to 1° intervals in southern geographic latitude (θ_{gs}). A corresponding scale for northern latitudes is shown, as are the positions of Siple and Roberval. In Figures 7 and 8, Siple and Roberval are slightly poleward of the centroids of the distributions. In Figure 8, 85% of the paths project onto the range $74° < \theta_{gs} < 77°$, which represents a latitudinal spread of $\simeq$330 km.

The relation of path radius to transmitter frequency during the FMDB is illustrated in Figure 9. Individual points represent measurements at discrete frequencies, usually at one or both of two FSK levels. Horizontal bars indicate measurements on frequency ramps. The solid curves show at what radius a given value of transmitter frequency is equal to specified fractions of the equatorial gyrofrequency.

The observations exhibit an inverse relation between path radius and frequency. This relation appears to be conditioned both by the small number of values of $f_{tr} > 0.5 f_{Heq}$ and by a concentration of values in the range 0.3–0.5f_{Heq}. Figure 10 summarizes this effect by a histogram of occurrence of values of f_{tr}/f_{Heq} in the FMDB.

A scatter plot of measured travel time τ_{tr} at transmitter frequency f_{tr} is presented in Figure 11. Frequency ramp data are denoted by a short bar. The data show on the average an inverse relation between f_{tr} and τ_{tr}. This is consistent with Figure 9, which shows that the lower frequencies tend to propagate on the longer paths.

Equatorial electron density along the paths studied in the FMDB is plotted in Figure 12. The densities, calculated by using the procedures developed by *Park* [1972], are characteristic of the outer plasmasphere and show the range of a factor of $\simeq$3 over which electron density in that region is known to vary during cycles of moderate disturbance and recovery [*Park,* 1974]. The wider range of density variation beyond $R/R_E \simeq 3.8$ is partly due to cases of propagation in the region

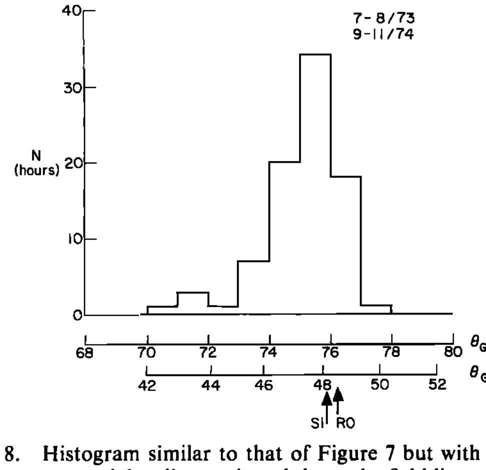

Fig. 8. Histogram similar to that of Figure 7 but with the information on equatorial radius projected down the field lines to geographic latitude at ground level. A hybrid geomagnetic field model (see text) was used for the mapping. The positions of Siple in southern and Roberval in northern geographic latitude are shown in the lower margin.

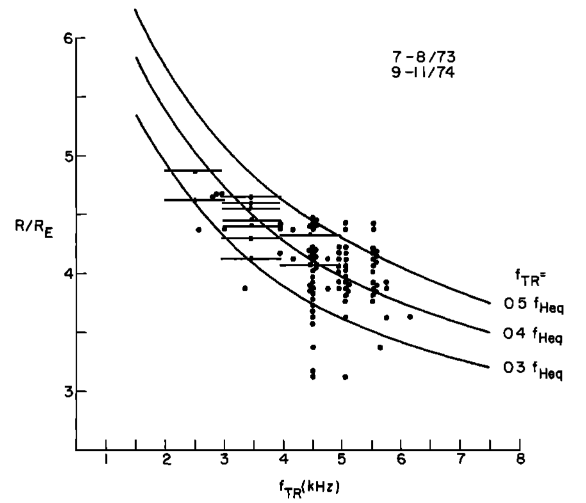

Fig. 9. Plot of inferred equatorial radius of Siple signal paths versus transmitter frequency. A horizontal bar indicates the range of a frequency ramp. Solid curves show at what radius a given value of transmitter frequency is equal to specified fractions of the equatorial gyrofrequency.

of plasmapause density gradients. On such paths, N_{eq} is less than nearby plasmasphere concentrations by a factor of up to $\simeq$2.

Under relatively quiet magnetic conditions, Siple signal paths are found within a region extending equatorially $\simeq$1–2 R_E inward from the plasmapause. The signals usually propagate on a single path or on several paths with closely spaced nose frequencies and travel times. This is illustrated in Figure 1, lower left, where a well-defined ramp is accompanied over part of its range by a component with travel time shorter by $\simeq$0.15 s or about 5%. The specific path locations appear to depend upon the prevailing distribution of ducts and the degree to which the ducts show evidence of frequency-dependent amplification, whistler mode echoing, and triggering of emissions by whistlers. Figure 13 shows electron density profiles deduced from multipath Siple whistlers on 2 days of transmitter signal reception at Roberval. In both cases there was a single prominent transmitter signal path; the data point representing this path is marked by a T (the dashed curves represent estimates of the general trends of the profiles). In the case of September 11, 1974, conditions were relatively quiet, and the path was well within the plasmasphere (the plasmapause was not defined in the data).

Under moderately disturbed conditions the plasmapause tends to be near the field lines of Siple/Roberval. In such cases the signal paths are frequently in the region of steep plasmapause gradients. A case of this kind representing moderate substorm activity on July 19, 1973, is illustrated in Figure 13.

Under severely disturbed conditions the plasmapause tends to be located equatorward of Siple/Roberval. Signal observations at such times are relatively rare; the paths observed thus far have been in the outer plasmasphere and have been detected during intervals of deep quieting that interrupt the disturbance activity.

DISCUSSION

It is clear that the properties of Siple signals observed at Roberval are closely linked to the magnetospheric conditions governing amplification of waves. While the Siple system radiates only of the order of 100–1000 W, the received signals are often as intense as the strongest whistlers and natural VLF emissions detected at the time. *Helliwell and Katsufrakis* [1974] report evidence that wave growth of the order of 30 dB commonly occurs on a Siple signal path. They show examples of spectral broadening of the Siple signals, of triggering of new frequencies, and of variations in growth as a function of frequency. Such effects are illustrated in Figure 1, lower panel, which shows triggering of new frequencies by 1-s pulses but not by frequency ramps. Variations in signal intensity with frequency are evident in the figure; both the ramps and the pulses are relatively faint at the edges of the 2- to 3-kHz band.

The effects of varying transmission parameters such as frequency f_{tr}, df_{tr}/dt, and pulse length are frequently of benefit to path analysis. A complex wave form will usually contain some elements for which travel time is particularly well defined. An example is the pulse at 2.2 kHz in Figure 1, lower panel, which is not complicated by triggering effects.

The dependence of the Siple signal observations on whistler propagation conditions has been evidenced in several ways.

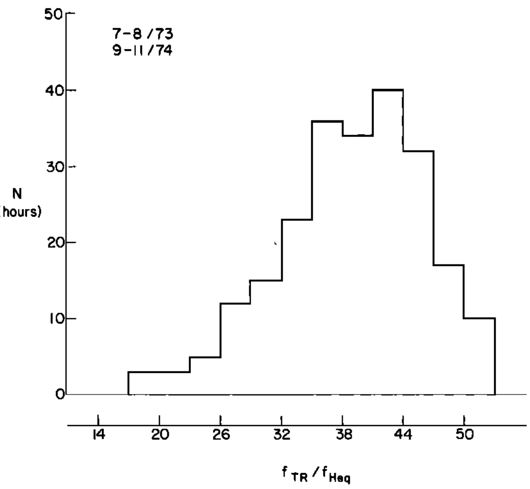

Fig. 10. Histogram of the number of observations of Siple signals at Roberval versus the ratio of transmitter frequency to path equatorial gyrofrequency.

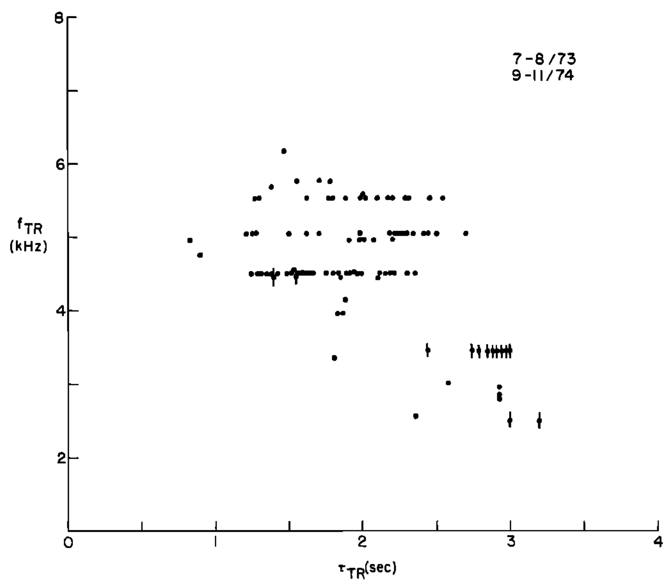

Fig. 11. Scatter plot of measured travel time τ_{tr} versus frequency f_{tr} of Siple signals observed at Roberval. Short vertical bars indicate measurements on frequency ramps.

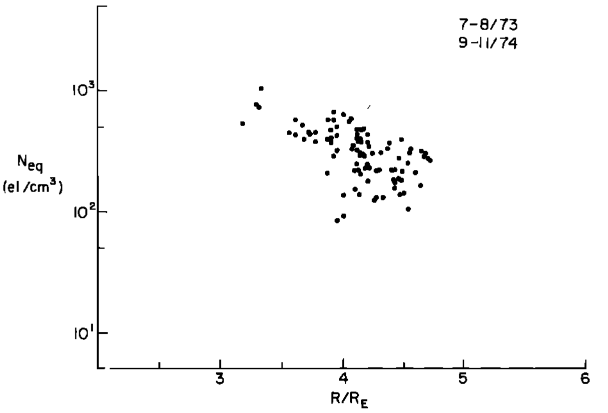

Fig. 12. Scatter plot of equatorial electron density along whistler paths followed by Siple signals.

The spectra of multipath whistlers received at Siple frequently contain a single component or closely spaced group of components that is prominent in terms of broad band signal strength, amount of triggering of VLF noise, and occurrence of echoing back and forth along the field lines. Siple signals observed at Roberval are frequently identified with this component or cluster of components. In particular, Siple signals tend to follow paths along which two-hop whistler propagation to Roberval occurs.

Whistler propagation beyond the plasmapause, while frequently observed, is rare in comparison to propagation within the plasmasphere [*Carpenter,* 1968*b*]. The Siple signal observations at Roberval show a similar effect; the paths thus far identified have been either within the outer plasmasphere or within the region of plasmapause gradients at positions between the mean plasmasphere and plasma trough levels. Although no case of propagation at the mean trough density level was found in the FMDB, such cases are expected to occur as the observations are continued.

The effect of an upper cutoff frequency of whistlers, apparently the result of unducting of whistler mode energy at half the local electron gyrofrequency, appears to be a controlling factor in Siple signal propagation. The distribution of observed path radii shown in Figure 7 agrees well on its right side with a predicted distribution (dashed) for which the governing assumption is a propagation cutoff at half the equatorial gyrofrequency.

Above moderate levels of disturbance and at middle to high latitudes, whistler occurrence statistics show an inverse relation to worldwide magnetic activity [*Helliwell,* 1965; *Allcock,* 1966]. Whistler rates tend to peak in the relatively long recovery periods following disturbances, as do the Siple signal statistics summarized in Figure 5. *McNeill and Andrews* [1975] found a similar relation in a statistical study of 8 years of observations of 18.6-kHz whistler mode signals from NPG (Seattle) propagating near $L = 2.5$ to Wellington, New Zealand.

The broad peak in Siple signal activity near dawn is consistent with reported near-dawn or predawn peaks in whistler activity [e.g., *Laaspere et al.,* 1963] and with earlier reports on observations at Eights, Antarctica, of signals from the 100-W Omega transmitter at Forest Port, New York. *Kimura* [1968] reported that observations of artificially stimulated emissions (ASE) produced at $L \simeq 3.6$ by the 10.2-kHz Omega signals were concentrated between 1000 and 1400 UT ($\simeq$0500–0900 MLT). Kimura also reported that occurrences of ASE produced by the $\simeq$ 1 MW NAA transmitter at $L \simeq 3.0$ exhibited a peak near dawn but that they also showed relatively high levels on the night side.

It is tempting to seek an explanation of the Siple occurrence data in terms of the night side injection and subsequent eastward drift of electrons appropriate for cyclotron resonance interactions with the Siple waves ($\simeq$1–20 keV). *McNeill and Andrews* [1975] found a weak but significant correlation between 18.6-kHz signal reception near $L = 2.5$ and the *Kp* index for the preceding 3–6 hours. When the Siple signals propagate in the region of large plasmapause gradients, signal activity often follows the fluctuations in VLF noise generated on the same or nearby paths. However, when the Siple signal paths are well within the plasmasphere, as occurred in the case of September 11, 1974, in Figure 13, relations of this kind are less obvious. In particular, no persistent relation has been found between onsets of signals at Roberval and indications of immediately preceding substorm expansions.

Reports on whistlers [e.g., *Laaspere et al.,* 1963] and on whistler mode propagation of fixed frequency signals in the 14- to 20-kHz range [*Helliwell,* 1965; *Allcock and McNeill,* 1966; *McNeill and Andrews,* 1975] have shown significant decreases in activity near sunrise and relatively low day side activity levels. The relatively frequent occurrence of Siple signals on the day side indicated in Figures 3 and 4 may be in part due to the closeness of the path entrance and exit points to Siple and Roberval, such that subionospheric propagation losses were smaller than those typical of the reported whistler and fixed frequency observations.

The relatively frequent detection of Siple signals during transmitter operation near 3 kHz is not yet well understood or documented. Typical antenna input power and radiation efficiency are reduced by $\simeq$5–10 dB at those frequencies; however, absorption for a single passage through the daytime *D* region has been estimated to be from $\simeq$2 to 5 dB less at 2.5 kHz than at 5.0 kHz [*Helliwell,* 1965; *Pitteway and Jespersen,* 1966]. Some of the success near 3.0 kHz may also be due to the availability at Siple of a video display of the VLF spectrum for purposes of frequency selection during the September–November 1974 portion of the FMDB and the fact that most of the cases for $f_{tr} < 3.5$ kHz in the FMDB occurred in this period. The success near 3 kHz is consistent with the fact

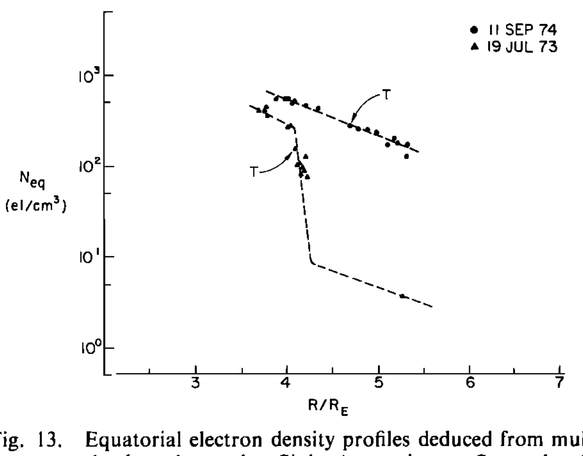

Fig. 13. Equatorial electron density profiles deduced from multicomponent whistlers observed at Siple, Antarctica, on September 11, 1974, at $\simeq$1905 UT and on July 19, 1973, at $\simeq$1140 UT. The estimated general trends of the profiles are indicated by dashed curves. The data point corresponding to a single prominent Siple signal path is marked by a T.

that the observed growth of Siple signals tends to be of the order of 30 dB, substantially larger than the frequency-dependent effects noted. It is also consistent with reported evidence that magnetospheric growth of ducted whistlers is a function of the ratio of frequency to equatorial gyrofrequency, growth usually being largest in the range f/f_{Heq} = 0.3–0.5 [*Carpenter,* 1968*a*]. According to the hybrid geomagnetic field model used (N. Seely, personal communication, 1975), f_{Heq} on the field line passing overhead of Siple at 100-km altitude varies from ≃8.8 kHz at 0000 MLT to ≃9.5 kHz at 1200 MLT. For f_{tr} = 3 kHz the range f_{tr}/f_{Heq} = 0.3–0.5 corresponds to field lines located (at 100-km altitude) from ≃50 km equatorward to ≃200 km poleward of Siple. For paths along these field lines the effects of latitudinal spreading losses from the magnetically east-west horizontal dipole antenna should be relatively small.

The occurrence of a peak in signal activity near the field lines of Siple and Roberval (Figures 7 and 8) may be attributed to the combined effects of antenna directivity and local minima in spreading losses in the earth-ionosphere wave guide, coupled with the fact that either the outer plasmasphere or the plasmapause are 'overhead' under most prevailing magnetic conditions. (For transmitter-receiver pairs at say, L = 7, an overhead peak would not be expected due to distance from the apparently favored outer plasmaspheric region of propagation. Beginning in 1966, the transmitter now at Siple was operated at Byrd Station (L ≃ 7) for several years, using a buried antenna. Signals were detected in the ionosphere overhead [*Siren,* 1974] but were not observed in the conjugate region, apparently because of low antenna efficiency and severe earth-ionosphere wave guide losses between the transmitter and duct entrance points in the outer plasmasphere.)

The rapid falloff on the low-latitude side of the histograms (Figures 7 and 8) is probably due to a combination of factors, including spreading losses, transmitter frequency limitations, and a tendency for 'active' ducts to occur near Siple/Roberval under a wide range of magnetic conditions. The transmitter was not operated between ≃6 kHz and 12 kHz because in that range the antenna impedance was too high for proper matching to the transmitter. For $R/R_E < 3.5$ the frequencies that are apparently favored for Siple signal reception, i.e., $0.3f_{Heq} < f_{tr} < 0.5f_{Heq}$ (Figure 9), are generally above 6 kHz.

With regard to duct activity, during quiet times the plasmapause tends to be poleward of Siple/Roberval, and a broad region of outer plasmaspheric duct activity is frequently centered near the station (e.g., case of September 11, 1974, in Figure 13). During moderately disturbed times the plasmapause is usually near Siple/Roberval, and on some such occasions (e.g., the case of July 19, 1973, in Figure 13) there is a concentration of duct activity in the region of plasmapause gradients.

The means of data selection and analysis may have contributed to the concentration of observed paths indicated in Figures 7 and 8. The visual search of spectrographic records for signals of well-defined travel time may have tended to discriminate against weak signals which represented propagation to end point latitudes near to or less than 74° (θ_{gs} in Figure 8).

CONCLUDING REMARKS

A tentative descriptive picture of the Siple/Roberval VLF transmission experiments is as follows: growth of the injected signals of the order of 30 dB is frequently observed [*Helliwell and Katsufrakis,* 1974]. The observed signal paths are located in the outer plasmasphere and region of steep plasmapause gradients; their equatorial radii are concentrated between 3.5 and 4.5 R_E, a range roughly centered on the Siple/Roberval field lines. Under these circumstances of minimal latitudinal spreading loss the conditions of signal observation appear to be strongly affected by the amplifying properties of the medium. Thus there is a dawn side activity peak and relatively high day side activity in spite of opposing propagation effects such as D region absorption. There is relatively frequent detection of transmissions near 2.5–3.0 kHz in spite of a 5- to 10-dB reduction in radiated power at these frequencies (compared to levels at ≃5 kHz). This result may be partly due to a falloff with decreasing frequency of absorption in the daytime D region.

The peak in signal activity near the Siple/Roberval field lines appears to be due to the combined effects of antenna directivity and of a local minimum in spreading losses, coupled with the fact that Siple/Roberval are typically located on field lines passing through the outer plasmasphere, a region of high ducted whistler and VLF noise activity. The sharp falloff of the path distribution on the high-latitude side appears to be due to the half gyrofrequency limit on ducted signal propagation. The sharp falloff near R/R_E = 3.5 on the low-latitude side appears to be due to the combined effects of spreading losses, a lack of transmissions in the 'favored' range of frequencies corresponding to 0.3–$0.5f_{Heq}$ at $R/R_E < 3.5$, and the availability of 'active' whistler ducts in the range R/R_E = 3.5–4.5 under the most frequently prevailing magnetic conditions.

The concentration of signal paths on field lines that are in latitude near Siple/Roberval and project to a ≃3° latitude range at ionospheric heights should be helpful in future correlative experiments in which sensors such as balloon X ray detectors need to be positioned optimally with respect to path end points.

While Siple signal detection at Roberval on paths with $R <$ 3.5 R_E is relatively rare, the special conditions of temporary quieting under which it tends to occur are becoming known. Thus the useful low-latitude range of the transmitting experiment is probably greater than the path statistics imply.

The analysis of Siple signal paths will be refined through additional analyses of the type reported here, through studies of signal amplitude, and through application of direction finding techniques. It is hoped to learn, for example, to what extent the signal paths are clustered in longitude. It is also hoped to compare the point at which a signal emerges from the ionosphere with the exit latitude predicted from dispersion analysis and a realistic geomagnetic field model.

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