JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. A9, PAGES 7051–7057, SEPTEMBER 1, 1983

Occurrence Properties of Ducted Whistler-Mode Signals From the New VLF Transmitter at Siple Station, Antarctica

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A new VLF transmitter called Jupiter was installed at Siple Station, Antarctica ($L \sim 4.3$) in 1979. A study has been made of the occurrence properties of magnetospheric signals from the transmitter detected at the conjugate station, Roberval, Canada and in the two-hop mode at Siple in 1980. The diurnal variation of the signals exhibited the previously noted major activity peak near dawn and a secondary peak near dusk. The former is believed to be due to a corresponding peak in resonant particle fluxes within the outer plasmasphere and the latter to destabilization of energetic particles that locally penetrated the evening bulge of the plasmasphere. The propagation paths followed by the better defined 2–4 kHz Siple signals had equatorial radii in the range $4 < L < 4.75$. This region maps at 100 km altitude to a north-south range of approximately ±150 km, centered on the latitude of Siple. The east-west range is believed to have been of comparable size. This concentration of signal paths is attributed to the effects of an injected wave power threshold for fast temporal wave growth in the magnetosphere, combined with spatial variation in ionospheric illumination by the transmitter. Also important was a concentration of operator-selected transmitter frequencies below 4 kHz, which permitted ducted propagation (i.e., $f < f_{Heq}/2$, where f_{Heq} is the equatorial gyrofrequency) on paths beginning nearly overhead at ~ 100 km altitude. The data are consistent with the existence of a relatively narrow north-south separation of ~ 100 km or less between the ionospheric point of wave injection and the field lines of the duct itself. The Siple transmitter has been able to induce magnetospheric wave growth and triggered emissions over the range $0.2 < f/f_{Heq} < 0.5$. These results differ from the reported concentration at $f/f_{Heq} \sim 0.5$ of discrete emission triggering by whistlers and by certain VLF transmitters. Enhanced Siple signal activity at ground stations has resulted from increases in transmitter power, a notable change from 1978 to 1980 being in the 2–3 kHz range, where Jupiter realized its largest (~ 10 dB) power advantage over Zeus.

1. INTRODUCTION

In 1979 a new VLF transmitter was installed at Siple Station, Antarctica ($L \sim 4.3$) for the purpose of conducting magnetospheric wave-injection experiments [*Helliwell and Katsufrakis,* 1974, 1978]. The transmitter, called Jupiter, is capable of operating at higher power (~ 7 dB) than the previous system, Zeus, and is also more flexible with respect to modulation. During the austral winter of 1980, signal receptions at the conjugate receiving station Roberval, Canada and in the two-hop mode at Siple itself were exceptional by comparison to data from previous years, both in terms of diurnal coverage and number of days of signal reception. One of the purposes of this paper is to describe and interpret the occurrence features of these data. Another purpose is to compare the occurrence rate of observed signals from Zeus with those from the higher-powered Jupiter system. An earlier occurrence analysis was performed on the Zeus data of 1973–1974 [*Carpenter and Miller,* 1976]; this reference, identified below as CM, provides background information for the present report and contains a description of our methods of using whistler data to estimate Siple signal path radii.

Paper number 3A0688.
0148-0227/83/003A-068805.00

2. EXPERIMENTAL RESULTS

Operating Frequencies

In this study the term 'transmitter frequency' refers to a reference frequency that was usually at the center of a 1-kHz-wide band. For Jupiter the radiated power at the edges of this band is down ~ 3 to 10 dB from the value at the reference frequency, largely due to detuning of the longwire antenna. For Zeus, maximum radiated power was usually at the upper edge of the band.

In order to identify optimum frequencies for transmission, the Siple operators employ aural and visual monitoring of the local VLF spectrum as well as test pulses and radiocommunications with the conjugate station, Roberval. In the May–August period of 1980, roughly 90% of the operator-selected frequencies were between 2 and 4 kHz, in spite of the fact that radiated power in that range was a factor of 5 or more below that achievable at ~ 5 kHz. This concentration between 2 and 4 kHz, as discussed later, appears to be at least partly the result of increased transmitter power.

Observations of Two-Hop Signals at Siple

In 1980 the Siple operators found that two-hop signals tended to occur whenever the Roberval observer reported one-hop activity. In some cases, estimated at about 30% of the observing hours, only Roberval detected signals, while

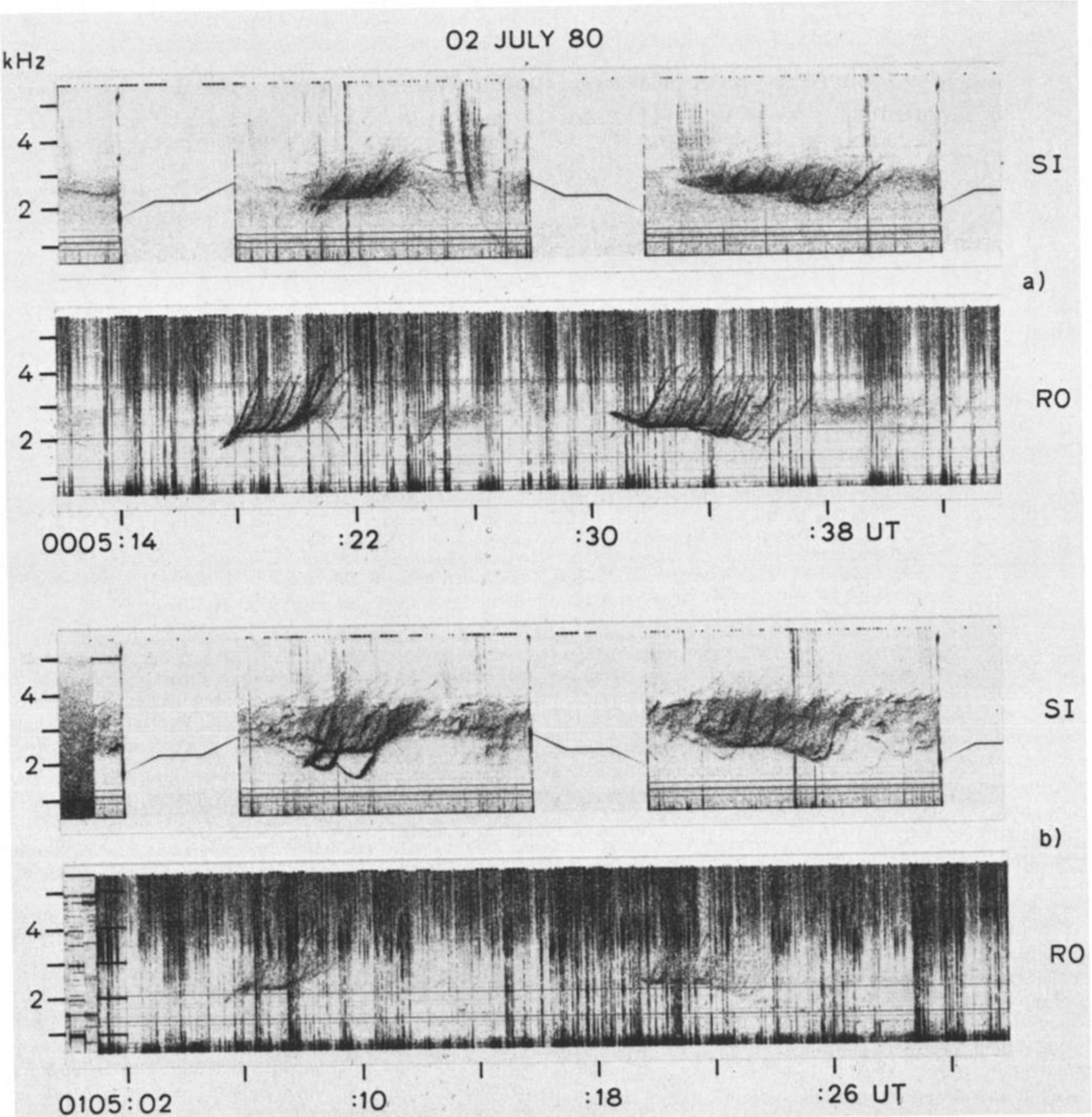

Fig. 1. Frequency-time records from the conjugate pair Siple, Antarctica/Roberval, Canada illustrating the observation of well-defined two-hop echoes at Siple. The frequency-time format of the transmitter signal is shown on the blanked portions of the Siple records.

in a smaller number of cases the only activity seen was at Siple. Figure 1 shows conjugate spectrograms illustrating (1) a case of strong signal activity at both stations and (2) one hour later, a case of signals better defined at Siple than at Roberval. The 'blanked' portions of the Siple records show the transmitter format. The relative weakness of the signal at Roberval at 0105 UT suggests an effect of ionospheric signal penetration, a topic that will be investigated in the future using HF sounding techniques.

Diurnal Variation of Observed Signals

Figures 2*a* and 2*b* show the distribution in universal time (below) and magnetic local time (above) of Siple signal activity in May–August, 1980. The UT hour was used as the basic interval, and any distribution of transmitter activity or signal observations during the course of an hour was treated as a single event. Figure 2*a* shows the number of signal observations in hours as a percentage of transmitting hours, while Figure 2*b* shows the absolute number of signal observations in hours. Both show the same major features, but the shape of the lower curve is considered more reliable. This is because an operator was available and prepared to transmit during essentially all hours in response to indications of favorable propagation conditions. Meanwhile, scheduled transmissions, not dependent for their inception on operator assessment of conditions, occurred mostly in the 0800–1600

UT period. This tended to reduce the success ratio in that period, and accounts for the main difference between the two figures. Figure 2*b* shows a relatively deep minimum centered just after local midnight and a rapid rise near 0400 MLT to a broad peak centered near 0700 MLT. After midmorning the activity decreased to a secondary minimum at ~1600 MLT and then increased to a secondary peak centered at ~1900 MLT.

Seasonal Variation in Duration of Signal Activity

Figure 3 shows a graph of the duration in hours of signal observations for the period May–December 1980. The longest uninterrupted sequence of observations in hours on a given day is represented, an observation being defined as the detection of signals during some part of an hour. The indicated seasonal variations in both numbers of days of activity and duration of observations are affected by reduced operator availability after August. However, there was extensive operator coverage in December during a balloon/rocket campaign, and the data for that period generally support the trends evident in the preceding months.

The data of Figure 3 show a general decrease from austral winter to summer in the number of days of activity. In November–December, most of the reception periods lasted no more than 1 hour, while in May–August most of the sequences were longer than 1 hour and many exceeded 5 hours.

Magnetic Conditions of Signal Observations

In the CM study of 1973–74 data and in the present work it was found that Siple signal detection preferentially occurred under quiet conditions. Signal reception under disturbed conditions did occur but tended to involve special circumstances such as propagation on paths with ionospheric endpoints located several hundred kilometers equatorward of the station, or on paths in the region of steep plasmapause gradients.

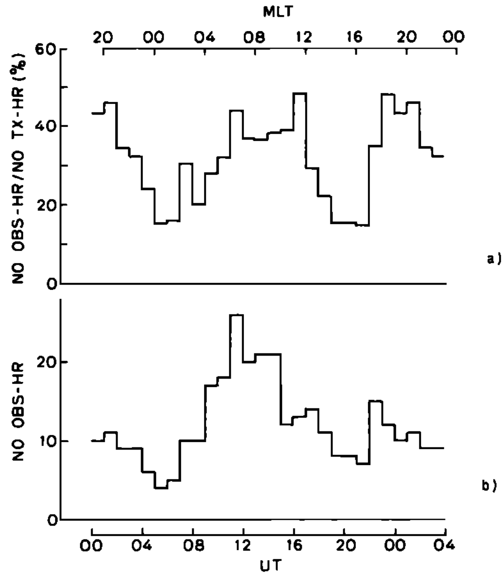

Fig. 2. Diurnal variation of Siple signal receptions in May–August 1980. (*a*) Number of hours of signal detection as a percentage of hours of transmission. (*b*) Number of hours of signal detection. The lower histogram is considered more reliable for reasons given in the text.

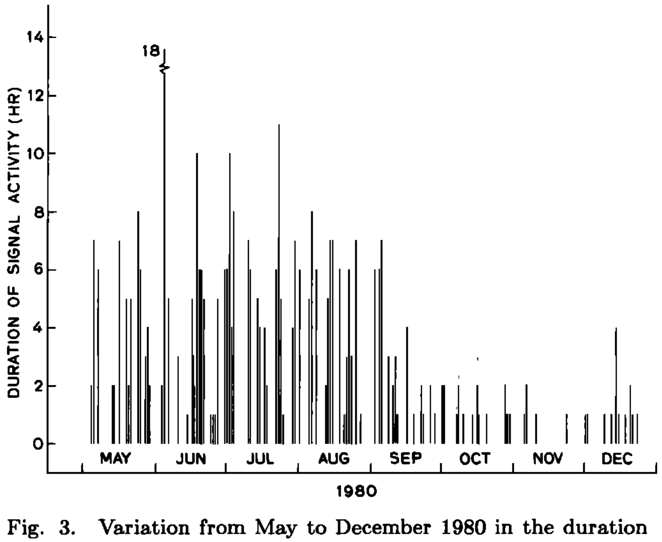

Fig. 3. Variation from May to December 1980 in the duration of periods of observed Siple signals. The duration in hours of the longest period for each day is displayed.

Figure 4 shows a plot of the percentage of successful signal detections in 3-hour periods as a function of the current 3-hour Kp index. The May–August 1980 period is represented; occurrences of transmissions and successful detections were determined on the basis of occurrence within the given 3-hour period without regard to duration. The numbers of transmissions for the various Kp bins are tabulated above. The figure helps to explain why Siple signals were detected at Roberval on 58% of the days in May–August 1980 but on only 28% in 1982. In 1980, daily ΣKp was less than 15 on 58 of 123 days, while in 1982 this occurred on only 20 days.

Path Locations and Electron Density Levels

Path equatorial radii estimates based on the measured properties of simultaneously propagating whistlers were performed for 21 periods on 12 days of strong signal activity in mid-1980. The number of separately analyzable paths in the various cases varied from one to three. Figure 5 shows (solid lines) the resulting distribution of equatorial radii. Also shown (dashed lines) is a histogram from CM for Siple data of July–August 1973 and September–November 1974. The greater width of the 1973–74 distribution is attributed to the fact that in that study, the received signals were distributed more widely in amplitude and degree of definition. Other differences in the two histograms are discussed below.

In Figure 5, the equatorial radius of the field line passing over Siple and Roberval at 100 km altitude as calculated by *Seely* [1977] is shown at ~4.4 R_E. A horizontal bar accounts for the range of expected variations within quiet days and for departures from exact conjugacy of the two stations. The range of path equatorial radii for 1980 projects to an ionospheric north-south range of ~±150 km at 100 km altitude over Siple/Roberval. The east-west range of path endpoints for strong signals appears to be roughly comparable in size, as indicated by direction-finding analysis on Siple signals from Roberval [*Seely,* 1977; *Leavitt et al.,* 1978] and from Palmer [*Tkalcevic,* 1983].

In the study of the 1973–1974 data, propagation was

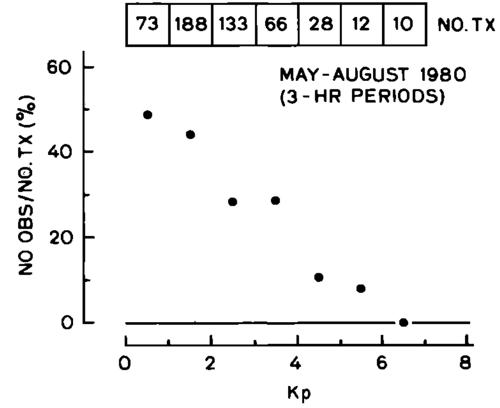

Fig. 4. Relationship for May–August 1980 between percentage of successful signal detections within 3-h periods and the current 3-h *Kp* index.

found to have occurred within the outer plasmasphere or within the region of plasmapause density gradients at density levels reduced by a factor of 2 or less from the outer plasmasphere level. This was also found to be true of the 1980 data. Most one-hop travel times at frequencies near 3 kHz were in the 2–3 s range and the inferred equatorial electron densities near $L = 4.5$ were in the range 200–400 el/cm^{-3}, typical of the outer plasmasphere. The corresponding parallel electron energies for gyroresonant interaction with the waves at the magnetic equator were 300 to 3000 eV.

Ratio of Transmitter Frequency to Equatorial Gyrofrequency

In the cases of relatively strong signals studied for 1980, the path radius tended to be 'overhead' at 100 km altitude for all frequencies within the 2–4 kHz range. The overhead path effect is illustrated in Figure 6, where a line represents the hypothetical curve that the data would follow if all signals propagated on a path with $f_{Heq} = 9.2$ kHz. This value is an 'average' of the 8.8 kHz and 9.5 kHz values calculated by *Seely* [1977] for midnight and noon conditions on the field line overhead with respect to Siple at 100 km altitude. The average of the 34 values of f_{Heq} determined for the data is 9.13 kHz.

In the CM report on the 1973–74 data from Zeus, the f/f_{Heq} observations had a broad peak near 0.4 and were largely confined to the 0.3–0.5 range. Figure 6 shows that with Jupiter in 1980, the normalized frequencies regularly extended below 0.3.

Comparisons of Results from Jupiter and Zeus

It is difficult to make quantitative comparisons of Jupiter and Zeus because of year-to-year variations in operating procedures and in experimental objectives and techniques and because of strong effects of magnetic activity noted above. However, there are indications that Jupiter has produced more detectable signals in a long-term average sense. Over the five years of Zeus' operations and for May–August, the average annual number of 'quiet' days (defined as ΣKp < 15) was 42, and the average annual percentage of days of Siple transmissions on which signals were detected was 24%. For the first 3 years of Jupiter's operations the corresponding average annual number of quiet days was also 42, and the average annual signal reception percentage was 33%, or 37% above the level for Zeus. This comparison must be treated with caution, since as noted, it involves two years, 1980 and 1982, with widely different magnetic conditions and widely different percentages of transmitting success.

A clearer indication of differences in the two systems appears in a comparison of Zeus in 1978 and Jupiter in 1980 in terms of success as a function of frequency. The comparisons, summarized in Table 1, were limited to May–August and to the 8-h period 0300–1100 MLT, during which relatively large numbers of routine transmisssions were performed in both years. They were further limited to the 2–3 kHz and 3–4 kHz frequency ranges, within which relatively large numbers of transmissions were made using both systems.

In the 3–4 kHz range, Zeus and Jupiter were successful in 30% and 48% of their transmitting hours, respectively. In the 2–3 kHz range, Zeus dropped to 10%, while Jupiter maintained a 41% level.

The differences in percentage success of Zeus and Jupiter as a function of frequency parallel their differences in power delivered to the antenna. In 1978 and 1980 the nominal total powers delivered to the antenna when operating at a fundamental of 5 kHz were respectively 30 kW and 120–150 kW, a ~6.5-dB difference, while at 2.5 kHz the corresponding values were 10 kW and 70 kW, an ~8.5-dB difference. The latter difference should probably be increased to ~10 dB or more, since the Zeus waveform below 4 kHz contained harmonic components that increased rapidly in amplitude with decreasing fundamental frequency [E. Paschal, personal communication, 1982].

3. DISCUSSION

Signal Path Latitude Distribution

Figure 5 shows that the 1973–1974 path data were centered ΔL ~0.3 equatorward of the overhead (at 100 km) Siple/Roberval field lines. This was attributed by CM

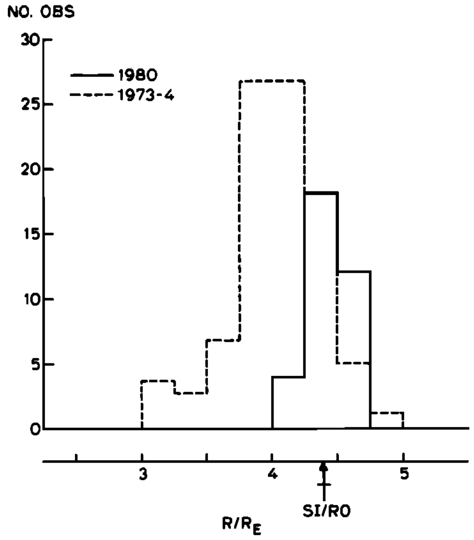

Fig. 5. Distribution of equatorial radii of Siple transmitter signal paths from the 1980 study of 21 periods on 12 austral winter days (solid line) and from the study of the July–August 1973 and September–November 1974 periods by *Carpenter and Miller* [1976]. The estimated position of Siple and Roberval stations with respect to the field line passing overhead at 100 km altitude is shown.

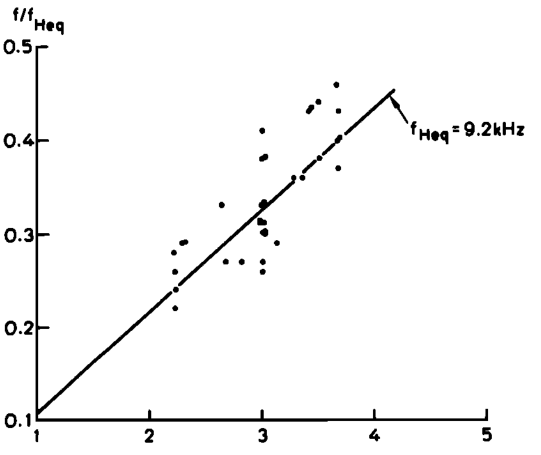

Fig. 6. Relationship between Siple transmitter frequency f and the ratio f/f_{Heq}, where f_{Heq} is the equatorial gyrofrequency of the transmitter signal path for the cases represented in Figure 5. The solid line represents the predicted behavior if all signals followed field lines with equatorial electron gyrofrequency 9.2 kHz. On the Siple meridian this field line is estimated to approximately overlie the station at 100 km altitude.

to an initial concentration of operating frequencies in the range 4.5–6.0 kHz, most of which exceed the 4.6 kHz half-gyrofrequency limit for ducted propagation on overhead paths. When, as the result of operating experience, transmitter frequencies were later concentrated below the 4.6 kHz limit, as in 1980, the equatorward shift disappeared.

The concentration of the 1980 distribution within a narrow latitude range of ±150 km can be attributed to several factors. The data represent 21 periods on 12 days of strong signal activity, as determined from spectrograms, and do not describe the distribution of all signals for which a path analysis could possibly be performed (as did the 1973–74 results). Path locations near Siple can be further explained by the report of *Helliwell et al.* [1980] on experiments in which observations of signals from multiple magnetospheric paths were made as the Zeus transmitter power was reduced in steps. In a case study the number of identifiable paths showing evidence of wave growth and triggered emissions progressively dropped from four to one and then to zero as transmitter power was reduced. This was interpreted in terms of an injected wave power threshold for fast temporal magnetospheric growth. Because of the antenna pattern and spreading losses, the injected signals on the more distant paths were the first to fall below the prevailing threshold.

Theoretically the ionospheric injection points of VLF waves are not expected to coincide with the 100-km projections of the ducts they excite, since the process of trapping within the duct may effectively take place at altitudes of order 1000 km [e.g., *Gorney and Thorne*, 1980; *Strangeways and Rycroft*, 1980]. From multistation crossed loop direction-finding measurements on whistlers near $L = 4$, *Strangeways et al.* [1982] report a case in which the offset was $\Delta L \sim 0.6$, or ~200 km in the magnetically north–south direction. The ionospheric entrance points of the Siple signals are not known, but a recent rocket experiment over Siple indicated a falloff in injected wave fields of ~10 dB within a distance of 100 km equatorward of the station [*Kintner et al.*, 1983]. This evidence plus the results of Figure 5 on signal path location suggest that the typical ionospheric separation of wave injection point and eventual field-aligned path was not greater than 100 km during the 1980 austral winter. Similar conclusions regarding the northern hemisphere exit regions of Siple signals were reached by *Seely* [1977] and *Leavitt et al.* [1978]. Siple transmitter signals thus appear to show smaller separation effects than would be expected from modeling studies and the goniometer data of *Strangeways et al.* [1982]. More study of this question is clearly required.

Diurnal Variation of Signal Activity

Referring to Figure 2, the diurnal variation in signal activity in May–August of 1980 is believed to depend upon resonant particle activity. The broad morning peak extending from ~0400 to 1000 MLT is probably related to particle trajectories that reach minimum equatorial radii near dawn as the result of magnetospheric convection. This peak is consistent with the more limited Zeus 1973–1974 observations of CM and is also consistent with an 0400–1000 MLT concentration of ground observations of wave growth on 100-W Omega transmitter signals [*Kimura*, 1968] as well as high-altitude ISEE satellite observations of triggering of emissions by ~10-kW Omega transmissions [*Bell et al.*, 1981]. The occurrence of favorable conditions on resonant particle fluxes

TABLE 1. Comparison of Zeus and Jupiter (May—August)

Frequency Range, kHz	Transmitter, Year	Number of Transmissions (hr)	(Number of Observations)/ (Number of Transmissions)
2—3	Zeus, 1978	129	10%
	Jupiter, 1980	83	41%
3—4	Zeus, 1978	128	30%
	Jupiter, 1980	192	48%

during this period is suggested by OGO 1 satellite observations of a broad prenoon peak in VLF emission amplitudes [*Dunckel and Helliwell,* 1969].

The secondary peak centered near 1900 MLT for May–August 1980 was not previously identified, partly because of limited transmitter operations in that time sector. We suggest the possibility that this is an effect of the penetration of the evening plasmasphere bulge region by drifting low-energy electrons, which then become a source for gyroresonant interactions. Evidence of such a penetration effect at other local times and under conditions of localized extensions of the plasmasphere radius was reported by *Smith et al.* [1981] and has been observed by one of the present authors (D. C.) during a December 1980–January 1981 rocket campaign at Siple Station.

There is a striking difference between the Siple diurnal variation of Figure 2, showing a predominance of dayside activity, and published data on natural whistler activity at mid-latitude stations, which show a concentration of activity under nighttime conditions [e.g.,*Laaspere et al.,* 1963; *Helliwell,* 1965]. Siple, at 76°S, experiences $\sim$24 hours of darkness during much of the May–August period, so that its diurnal curve is to a large extent independent of the day-night variations in ionospheric absorption that affect whistler statistics.

Magnetic and Seasonal Conditions of Siple Signal Observations

The problems of understanding why both whistler and Siple signal activity tend to be relatively low during periods of magnetic disturbance and in the region outside the plasmapause have not been solved. Transmitter experiments at varying power levels, coordinated with satellite and ionosonde observations, should provide new information both on the importance of injected wave level in the wave growth and emission triggering process, as well as on the occurrence of ducted propagation and on how it may be interrupted or inhibited by disturbance phenomena. The austral summer falloff in signal activity (e.g., October–December, Figure 3) is probably due to effects of increased ionsopheric absorption. For the Siple observers, both the injected wave and returning two-hop echo are subject to these effects. The data of Figure 3 need to be supplemented by seasonal measurements made under more nearly uniform operating conditions.

Normalized Frequencies of Observed Wave Growth

In Figure 6 the observed broad distribution of f/f_{Heq} values between 0.2 and 0.5 differs markedly from what had been expected from observations of triggering of emissions by both fixed frequency transmitter signals and whistlers, namely, a concentration near 0.5 [e.g.,*Carpenter,* 1968]. In the case of fixed frequency transmission signals from NAA (Cutler, Maine) this concentration is believed to be due to a combination of factors that do not affect the Siple experiments, including (1) location of the transmitter at $L \sim 3.2$, 200 km poleward of the field line region within which its frequency (17.8 kHz) meets the half-gyrofrequency condition for transequatorial guiding within an enhancement duct and (2) location of the transmitter in the slot region where energetic electron fluxes tend to fall off steeply with decreasing L [e.g., *Vette et al.,* 1966]. (In 1963, when the NAA frequency was increased from 14.7 kHz to 18.6 kHz, production of triggered emissions dropped significantly [*Carpenter and Lasch,* 1969].) Both of these factors favor interactions on the nearest equatorward paths of interhemispheric propagation.

In the case of whistlers the concentration of triggered emission activity at $f/f_{Heq} \sim 0.5$ appears to be due to (1) relatively rapid variation of the signal delay with frequency near the whistler nose frequency of minimum group delay ($f/f_{Heq} \sim 0.4$), such that the length of the wave-particle interaction region is relatively short and the efficiency of phase bunching by the waves correspondingly reduced [*Helliwell,* 1970; *Bell and Inan,* 1981], and (2) the abrupt upper intensity cutoff of whistlers at $f/f_{Heq} \sim 0.5$ [*Carpenter,* 1968]. At the cutoff an emission is frequently generated; it is believed to be a free-running continuation of the upper part of the whistler in the manner of the 'termination triggering' by Siple signals discussed by *Helliwell and Inan* [1982]. Well below the whistler nose, at $f/f_{Heq} < 0.2$, there is another, less well documented concentration of emission triggering within the plasmasphere. *Helliwell* [1965] and *Dowden* [1971] have shown examples of this.

The actual magnetospheric response to Siple signals as a function of f/f_{Heq} varies widely in time, and because of prevailing antenna tuning and efficiency characteristics, has not been explored in the range below $f/f_{Heq} = 0.2$. Activity is often concentrated at frequencies coincident with or near existing bands of noise or whistler activity. Observed signals are frequently limited to bands less than 1 kHz in width but on occasion are detected over a several-kHz range.

4. CONCLUSIONS

1. During the austral winter of 1980, the propagation paths followed by the better-defined 2–4 kHz Siple signals had equatorial radii in the range $4 < L < 4.75$. This region maps at 100 km altitude to a north-south range of approximately ±150 km centered on the latitude of Siple. The east-west range is believed to have been of comparable size. This concentration of signal paths is attributed to the effects of an injected wave power threshold for fast temporal wave growth in the magnetosphere, combined with spatial variation in ionospheric illumination by the transmitter. Also important was the concentration of operator-selected transmitting frequencies below 4 kHz, such that ducted propagation on paths beginning nearly overhead at 100 km altitude was possible. The data are consistent with there being a relatively narrow north-south separation, of 100 km or less, between the ionospheric point of wave injection and the field lines of the duct itself. A larger separation, of order 200 km, has been reported from whistler observations by *Strangeways and Rycroft* [1982]. Further study is needed in order to reconcile the differences.

2. Transmitter signal observations were distributed over all local time periods during the austral winter of 1980. A major peak in activity near local dawn appeared to be due to a corresponding peak in resonant particle fluxes within the outer plasmasphere, while a secondary peak near dusk is believed to be attributable to the destabilization of energetic particles that locally penetrated the evening bulge of the plasmasphere. Evidence of such penetration has been found during observations of localized plasmasphere extensions other than the evening bulge. Differences between the predominantly dayside Siple signal activity and predominantly nightside middle latitude whistler activity

are attributed to the greater dependence of Siple signal observations upon magnetospheric amplification, as compared to the strong dependence of the whistler data upon ionospheric absorption.

3. The Siple transmitter at $L \sim 4.3$ has been able to induce magnetospheric wave growth and triggered emissions over the range $0.2 < f/f_{Heq} < 0.5$, where f is the transmitted frequency and f_{Heq} is the path equatorial electron gyrofrequency. These results differ from reported concentrations at $f/f_{Heq} \sim 0.5$ of discrete emission triggering by whistlers and by fixed frequency VLF transmitters. In the case of whistlers the differences are believed to be an effect of the rapid time variation of the signal frequency near the whistler frequency of minimum group delay, as well as to 'termination' triggering at the whistler half-gyrofrequency upper intensity cutoff. In the case of the fixed frequency transmitter NAA, the differences are attributed partly to the proximity of the transmitter ($L \sim 3.2$) to the 'slot' region of rapid decreases with latitude in energetic particle fluxes and partly to the 200 km separation of NAA from the nearest field lines along which ducting to the conjugate region is theoretically possible.

4. Enhanced Siple signal activity at ground stations has resulted from increases in transmitter power, a notable change from 1978 to 1980 being in the 2–3 kHz range, where Jupiter realized its largest (~ 10 dB) power advantage over Zeus.

5. In continuing need of solution are problems of the dropoff in signal activity during periods of magnetic disturbance and in the region outside the plasmapause. The role of transmitter power in these relations is especially interesting.

Acknowledgments. We are grateful to J. P. Katsufrakis for his management of Stanford's VLF field programs, and to E. W. Paschal and W. J. Trabucco for their engineering work on the Zeus and Jupiter transmitters. Special thanks go to J. Billey and M. Dermedziew for their outstanding efforts as field engineers at Siple in 1980. We thank R. A. Helliwell, T. F. Bell, and U. S. Inan for helpful discussions, P. Pecen for assistance in data analysis, and K. Faes for preparation of the typescript. This research was supported by the Division of Polar Programs of the National Science Foundation under grants DPP80-22540 and DPP80-22282.

The Editor thanks H. C. Koons and J. C. Siren for their assistance in evaluating this paper.

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(Received June 25, 1982;
revised March 22, 1983;
accepted May 2, 1983.)