JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A5, PAGES 4383–4388, MAY 1, 1985

A New VLF Method for Studying Burst Precipitation Near the Plasmapause

D. L. CARPENTER, U. S. INAN, AND E. W. PASCHAL

Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford California

A. J. SMITH

British Antarctic Survey (NERC), Cambridge, England

VLF signals in the 2–4 kHz range transmitted from Siple Station, Antarctica ($L \sim 4.3$), and received at various Antarctic locations have been used to detect the occurrence of burst precipitation of electrons ($E \geq 50$ keV) into the nighttime lower ionosphere. The receiving stations, each ~1400 km from Siple, were located to the north at Palmer ($L \sim 2.3$), to the east at Halley ($L \sim 4.3$), and to the south at South Pole ($\Lambda \sim 74^{\circ}$). Rapid changes in the received phase and amplitude of the Siple signal ("Trimpi events") were observed in conjunction with the reception of one-hop whistlers. In one case involving propagation paths lying poleward of the plasmapause, amplitude decreases by ~20% in ~2 s, decaying in ~7 s, were recorded simultaneously at Halley and South Pole. Post facto analysis of the South Pole records using a new digital processing scheme showed corresponding fast phase advances of ~15 μs. In a case of phase perturbations at Palmer, the Siple signal path crossed the plasmapause projection, and the associated whistlers propagated in the outer plasmasphere. Phase measurements appear to be a particularly sensitive means of detecting burst precipitation activity under experimental conditions of the kind described. The length and spatial distribution of the signal paths provide a basis for studying the occurrence and approximate location of burst precipitation in regions outside the observing range of most instruments used for detection of precipitation. Direction finding on correlated whistler events as well as dispersion analysis may be used to increase the spatial resolution of the method.

1. INTRODUCTION

Studies of burst precipitation into the ionosphere at auroral and subauroral latitudes near the plasmapause projection have yielded significant new results in recent years. For example, there is mounting evidence of an ionospheric source for certain classes of ULF pulsations that are closely correlated with impulsive aurorae and ionospheric absorption events [e.g., *Engebretson et al.*, 1983; *Arnoldy et al.*, 1982; *Oguti et al.*, 1984], and there is also developing evidence that discrete VLF emissions play a causative role in the generation of these ULF events, through the particle precipitation that the emissions induce [*Armstrong et al.*, 1983].

However, much remains to be learned about the location and extent of precipitation regions and about their dynamics. One attractive means of extending our knowledge of these subjects involves use of subionospheric VLF transmissions from a source to multiple receivers. Figure 1 shows such a configuration, in which signals from the experimental VLF transmitter at Siple, Antarctica ($L \sim 4.3$), are received at Palmer, Halley, and South Pole stations. Assuming that the phase and/or amplitude of the received signals is sensitive to precipitation activity along or near the corresponding great circle paths, it should be possible, by comparing data from the several receivers, to study the spatial distribution of the activity. Because the nominal VLF reflection height is in the range 80–85 km under typical nighttime conditions, the precipitating energies involved would be expected to be above ~50 keV.

In principle, the proposed method is an extension of the single-station methods that have recently been used to study burst effects within the plasmasphere near L=2 [*Carpenter and LaBelle*, 1982; *Leyser et al.*, 1984]. In this previous work, attention was focused upon whistler-associated amplitude and phase perturbations occurring well equatorward of the plasmapause projection on signals from communication and radio-navigation sources in the 10–24 kHz range [*Helliwell et al.*, 1973; *Lohrey and Kaiser*, 1979]. Typical changes on paths 2000–10,000 km in length have been found to be ~1-2 dB in amplitude and a few microseconds in phase delay. The changes, called "Trimpi events," typically develop within ~1-2 s and decay over periods of ~10-100 s. However, a case of signal changes observed at conjugate stations just outside the plasmapause in association with whistler-triggered chorus bursts has also been reported [*Dingle and Carpenter*, 1981].

The proposed experimental approach is in a sense well established; multiple VLF paths ranging widely in latitude and longitude have previously been used to detect a variety of precipitation effects, with emphasis upon polar cap absorption events (PCA's) and substorm effects [e.g., *Westerlund and Reder*, 1973; *Potemra and Rosenberg*, 1973]. However, the method has not been extensively applied to burst precipitation events occurring near to and poleward of the plasmapause, nor has an experimental transmitter, such as that at Siple Station, been utilized.

Paper number 4A8377.
0148-0227/85/004A-8377$02.00

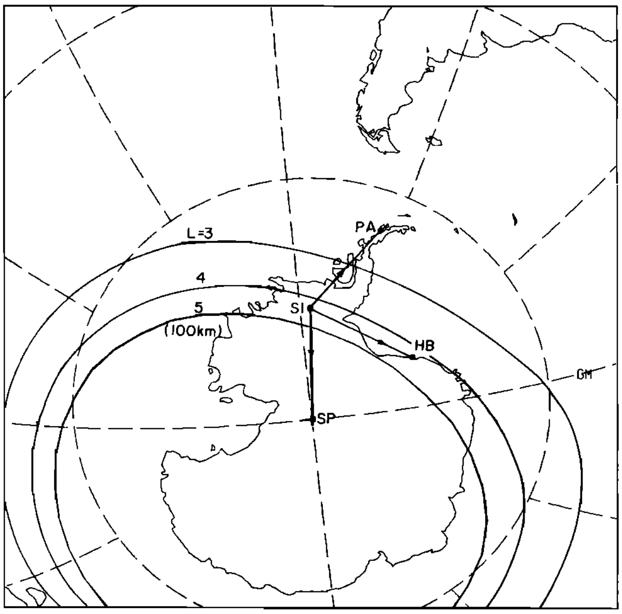

Fig. 1. Map showing subionospheric signal paths from the Siple (SI), Antarctica, VLF transmitter to Palmer (PA), Halley (HB), and South Pole (SP) stations in the Antarctic.

The purpose of this brief report is to describe initial observations of burst precipitation effects on Siple transmitter signals propagating (1) on paths lying poleward of the plasmapause projection and (2) on a path originating outside the plasmapause and terminating within the plasmasphere. The data from Halley and South Pole were recorded on magnetic tape in July 1982. The tapes were later processed for amplitude information using a narrow band filter. The South Pole data were also processed for both amplitude and phase variations using a digital processing scheme which includes compensation for tape recorder speed variations [*Paschal and Helliwell*, 1984]. The data from Palmer were recorded in May 1983 on an eight-channel correlation chart connected to a modified phase-tracking receiver.

2. OBSERVATIONS

Signal Perturbations on Paths Poleward of the Plasmapause

Between 1300 and 2200 UT on the six days July 12–17, 1982, Siple transmitted an unmodulated 3.79-kHz signal for the purpose of investigating the effects of the cusp on subionospheric propagation to South Pole Station. Whistler-associated burst precipitation effects on the signal were detected simultaneously at Halley and South Pole stations on July 16. This day followed a major magnetic storm on July 13–14, such that during local afternoon on July 16, the plasmapause was well equatorward of Halley and Siple. From whistler evidence, $Lpp < 3.7$; thus both propagation paths (Figure 1) lay entirely poleward of the plasmapause.

Figures 2*a* and 2*b* show Halley and South Pole observations, respectively, of two fast amplitude decreases (~20% in ~2 s) in the Siple field strength near 2145 UT. Figures 2*c* and 2*d* show corresponding 0–5 kHz spectrograms. Arrows between Figures 2*b* and 2*c* show the approximate times of the first observed whistler component (Figure 2*c*) and the onsets of the signal perturbations. Comparison of the amplitude records and spectrograms shows that the amplitude decreases began ~1.5 s after the initial detection of the whistler in the 3–4 kHz range. The ~2-s development time of the decreases is in the upper range of observations reported previously for paths lying equatorward of the plasmapause [*Helliwell et al.*, 1973], while the ~7 s decay time is faster than the ~30 s that was previously observed.

From nose frequency analysis the whistlers are inferred to have traveled on multiple paths outside the plasmapause, in the range $L = 3.7$–5.5. The L range in which the burst precipitation occurred cannot be located with certainty; analysis of the spectrograms suggests that the precipitation was associated with a whistler component propagating at $L=4.7 \pm 0.3$ and with bursts of band-limited (2–3.5 kHz) noise triggered by that component; the periodicity of the hiss (~2.5 s), apparent in Figure 2*c*, is interpreted as a two-hop whistler mode propagation delay. A direction-finding (goniometer) analysis of the Halley records suggests that the band-limited noise emerged from the ionosphere to the southwest of the station, in the direction of South Pole Station (see Figure 1).

The same or similar whistlers were observed at the two stations, but those at South Pole were fainter, presumably due to attenuation on subionospheric path segments across L shells to South Pole (Figure 1). The amplitude difference of ~18 dB between the Siple signal levels at Halley and South Pole is qualitatively consistent with the difference in whistler and emission amplitudes.

The amplitude record of Figure 2*b* was made using a narrow band (30 Hz) analog filter. In order to measure corresponding phase perturbations in the presence of fluctuations in tape recorder speed, we have used a new technique reported by *Paschal and Helliwell* [1984], in which several minutes of broadband analog data are digitized at a 25.6-kHz rate. The discrete Fourier transform is calculated for successive blocks of digitized data to give spectral information as a function of time. The phase of a constant-frequency pilot tone recorded on the data tape is measured in each spectrum and used to correct the spectrum for errors due to tape speed variations, yielding the amplitude and phase at any desired frequency within the passband, in this case at the Siple transmission frequency.

Figures 3*a* and 3*b* illustrate the amplitude and phase of the Siple transmission received at South Pole during the interval of Figure 2, obtained using the Paschal method. Unfortunately, the Halley pilot tone was not sufficiently stable for extraction of similar phase information. The similarity between Figures 3*a* and 2*a* shows that the digital and analog methods are equivalent with regard to amplitude.

Figures 2*a* and 2*b* show two occurrences of simultaneous and comparable amplitude decreases at Halley and South Pole. During both events, South Pole detected a rapid (~2 s) phase advance of about 15 μs, followed by an ~7-s recovery. The burst signature is much better defined on the phase plot (Figure 3*b*) than on the amplitude plot (Figure 3*a*), although the smoothing time constant is the same for both. The superior signal-noise ratio of the phase data in this case is illustrated on the records of Figure 3*c* and 3*d*, which show a longer period of time on a compressed time scale. In addition to the several increases of ~10–15 μs (marks above Figure 3*d*) a series of smaller events of ~2 μs can be identified, each in connection with a VLF event. The times of the

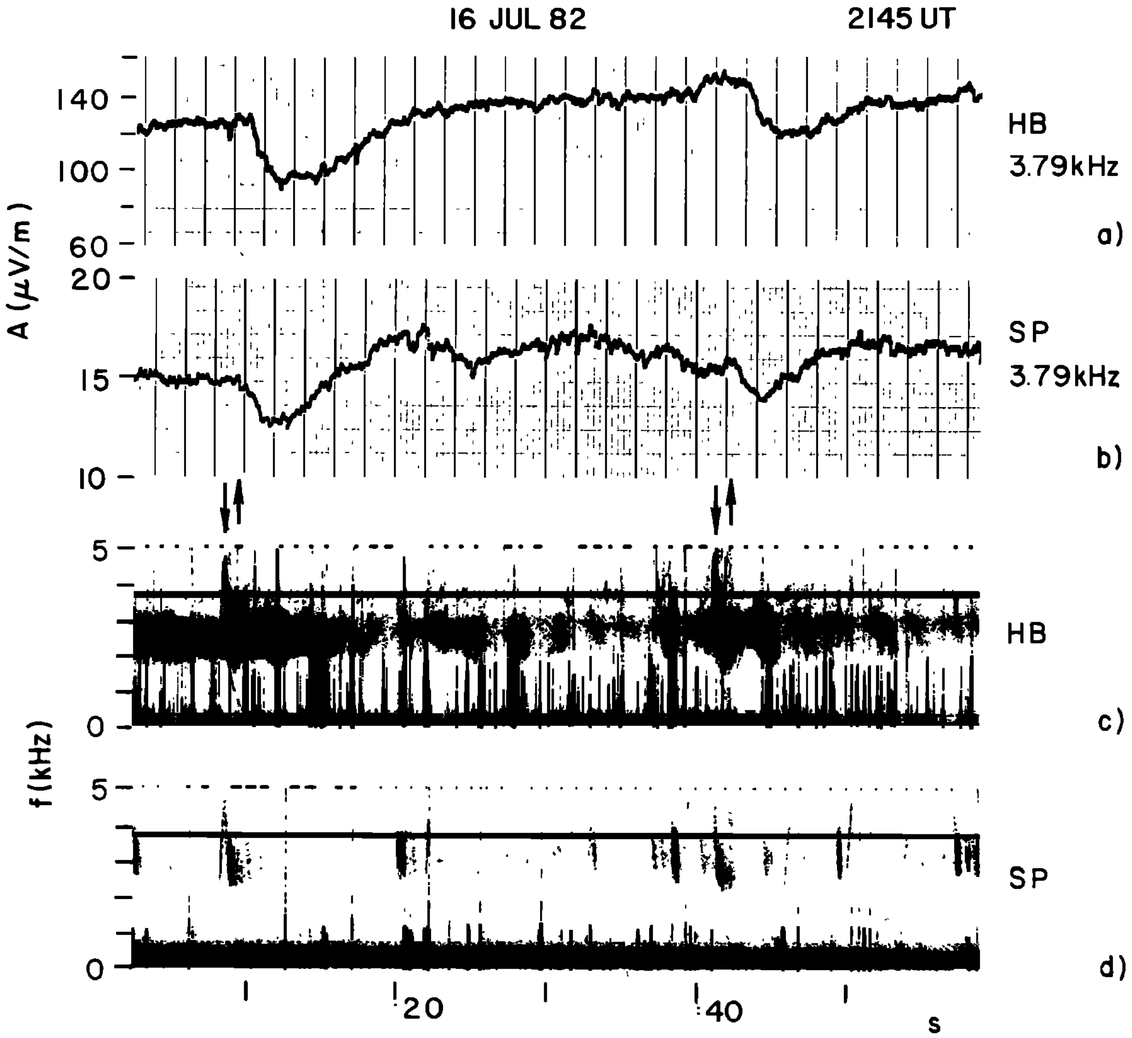

Fig. 2. Two whistler-associated amplitude perturbations on 3.79-kHz signals from Siple Station, observed simultaneously at Halley and South Pole. (*a*) Halley narrow band (30 Hz) amplitude at 3.79 kHz. (*b*) Same for South Pole. (*c*) Halley spectrogram showing the whistlers that were correlated with the two principal amplitude decreases. (*d*) Same for South Pole.

more noticeable of these are indicated by arrows below Figure 3*d*. In general, these changes are much less well defined, if recognizable at all, on the amplitude charts.

The whistler-correlated changes just described were only one of a variety of amplitude and/or phase changes on the Siple signal observed during ~7 hours of transmission on July 16. At South Pole there were changes due to a sudden commencement at 1529 UT, as well as fluctuations in association with discrete VLF emission elements. At both South Pole and Halley there were changes associated with variations in the intensity of quasi-continuous magnetospheric VLF noise. In one case occurring 5 hours earlier, an amplitude change similar to those of Figure 3 was observed at Halley and South Pole, but without clear evidence of a correlated wave event.

Perturbations on a Path Crossing the Plasmapause

Whistler-related perturbations on Siple signals received at Palmer have been observed; Figure 4, an enlarged photograph of chart recordings made at Palmer on May 24, 1983, shows a 20-min series of such events. The lower panel shows fast phase advances of ~8 μs on a 2.45-kHz CW signal, followed by recoveries lasting ~30 s. These occurred in time correlation with whistlers, which are indicated on the upper record of 2–4 kHz as positive spikes. The events most clearly identifiable as whistlers show a negative spike as well, followed by a slow recovery. (This effect is evidence of temporary suppression of a background noise by the whistler, as discussed by *Gail and Carpenter* [1984].) Vertical lines show the temporal correlation between representative whistlers and fast phase advances. In this case, amplitude variations of the Siple signal were not well defined. (A postanalysis of Siple signal phase by the Paschal method could not be made in this case, due to lack of an appropriate reference tone on the data track.)

Figure 5 shows examples of whistlers recorded ~20 min prior to the period of Figure 4. At this time the phase advances were more closely spaced, exhibiting only partial recovery between the stronger events. Two of the stronger whistlers are shown, with times of origin (causative atmospherics) aligned with the arrow below Figure 5*b*. The Siple signal appears as a horizontal line at 2.45 kHz. The whistlers

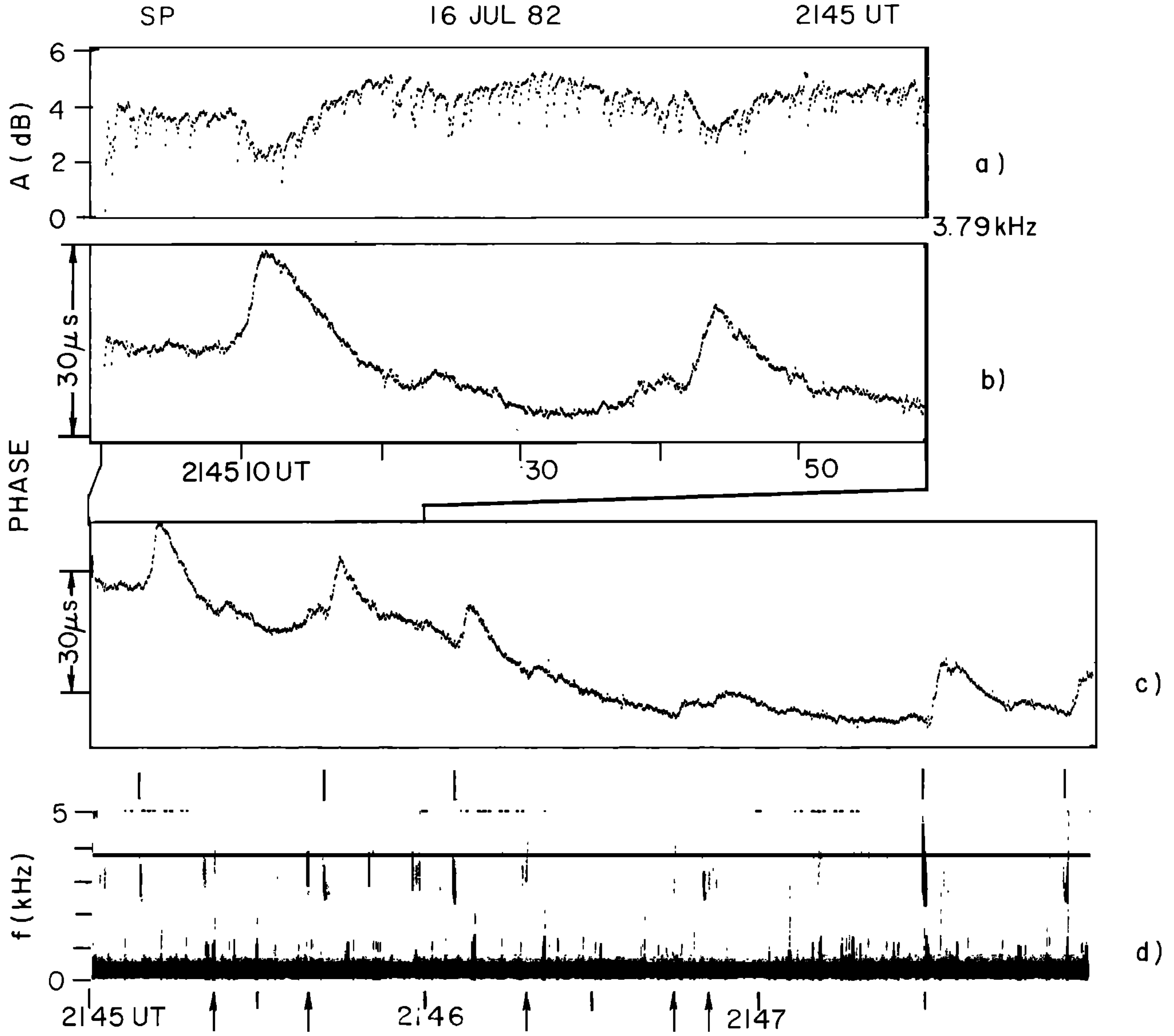

Fig. 3. Details of phase and amplitude changes observed at South Pole Station at the time of the events of Figure 2. (*a*) Amplitude of the Siple signal at 3.79 kHz, obtained by digital processing of the broadband records using the method of *Paschal and Helliwell* [1984]. (*b*) Phase of the Siple signal obtained by digital postprocessing. (*c*) Phase of the Siple signal during a longer interval. (*d*) South Pole VLF spectrogram corresponding in time to the phase record of Figure 3*c*. Tick marks above the panel show the whistler events correlated with the larger phase perturbations.

exhibit multiple paths characteristic of propagation within the plasmasphere. Two comparatively strong components are present; dispersion analysis indicates that they propagated at $L \sim 2.9$ and $L \sim 3.2$. The second strong component (arrow in Figure 5*b*) exhibited high amplitude well below the earth-ionosphere half-wave cutoff frequency of ~1.8 kHz, suggesting that the component emerged from the ionosphere within a distance of the order of 1000 km of the receiver. At ~1 kHz this component would have been in gyroresonance at the equator with low pitch angle electrons of ~100 keV energy.

The presence of a plasmapause with ionospheric projection within the range L=3.2–3.8 is indicated by Siple whistlers recorded within the preceding several hours and by the Palmer whistlers of Figure 5. Panel *a* shows two forms of third-hop echo (arrows), the first due to energy coupled after the first hop to a path at $L \sim 3.8$ outside the plasmapause, and the second due to conventional plasmasphere echoing along the path of the component marked in Figure 5*b*. We thus infer that the plasmapause was located in the L=3.2–3.8 range, and that the principal precipitation region was close to the plasmapause, and at L values that correspond to midway along the Siple to Palmer path.

3. DISCUSSION AND CONCLUDING REMARKS

Experiments such as those described here can provide important extensions of existing methods of studying burst precipitation. The signal path segments can be short enough to place rough geographical limits on the ionospheric region or regions affected, but long enough to be sensitive to ionospheric perturbations occurring over substantial distances

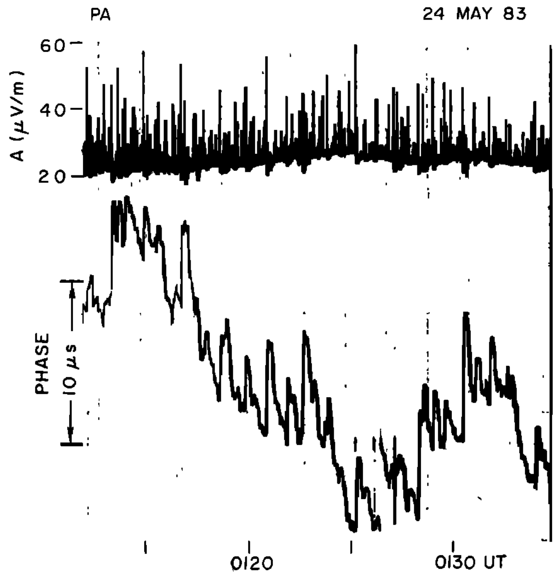

Fig. 4. Palmer chart records showing phase perturbations on a 2.45-kHz signal from Siple, correlated with whistlers of the type illustrated in Figure 5. The whistlers appear as amplitude spikes on the upper record. Vertical lines connect representative examples of the associated whistlers and fast phase increases.

and in regions outside the viewing range of most other sensors.

The reported observations are consistent with previous observations of subionospheric VLF signal changes associated with whistlers propagating within the plasmasphere [e.g., *Helliwell et al.*, 1973; *Lohrey and Kaiser*, 1979; *Carpenter and LaBelle*, 1982] and outside the plasmapause [*Dingle and Carpenter*, 1981]. They are also consistent with the observation that within the plasmasphere, whistlers correlated with burst precipitation are usually well defined and free of triggered emissions, while in the plasmatrough region, the associated whistler component is often poorly defined and followed by a burst of triggered noise [*Rosenberg et al.*, 1971; *Helliwell et al.*, 1980].

The new method should be helpful in resolving as yet unanswered questions about the spatial distribution of precipitation regions associated with whistlers. For example, in the July 16 case of Figures 2 and 3, the associated VLF signal propagated at $L = 4.7 \pm 0.3$. (The ± 0.3 range of uncertainty in L is attributed to uncertainty in the field-line plasma distribution model used in the estimates of whistler path equatorial radius, and the use of a dipole geomagnetic field model in the calculations.) The Halley direction-finding data, in combination with the information on path L value, suggest that the precipitation region was relatively close to the station, within 400 km in a southwesterly direction. However, the South Pole Station signal perturbations probably occurred much further to the west, near Siple, suggesting that precipitation was distributed over an extended longitude region. Differences in detail of the precipitation-induced effects at the two stations are suggested by the South Pole amplitude records of Figure 2, which contain not only the two large events seen at Halley, but also evidence of small decreases near 2145:22 and 2145:38 UT, which were not apparent at Halley. As noted above, these and other similar events are more readily seen in the South Pole phase records of Figure 3. Such a longitudinal extension of

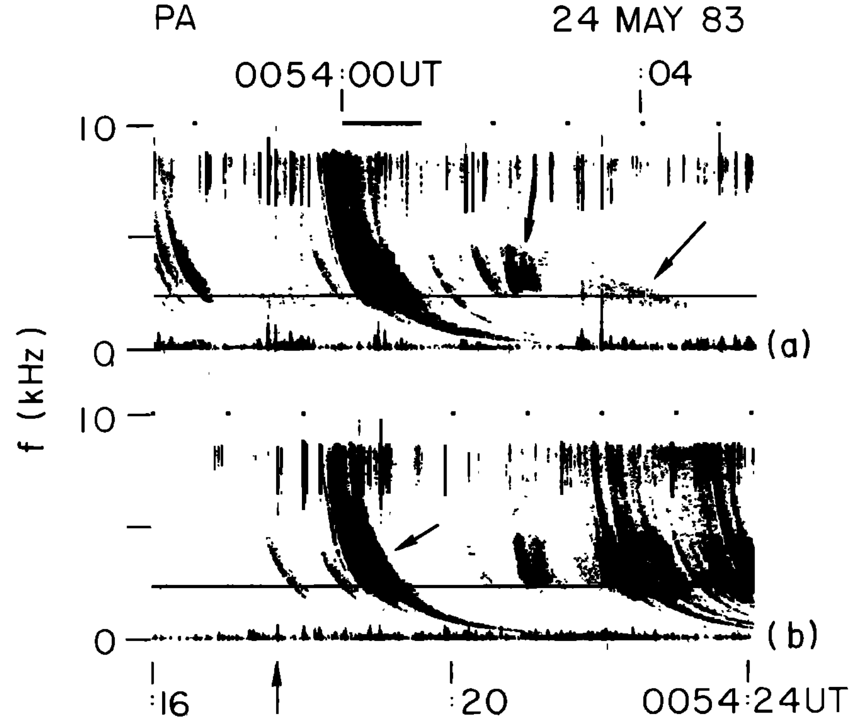

Fig. 5. Spectrograms of whistlers recorded at Palmer at the time of phase perturbations on 2.45-kHz signals from the Siple transmitter. The two events are aligned in time with respect to the time of the causative atmospherics (arrow in lower scale). The components marked by the first arrow in the upper panel provide evidence of coupling of waves from inside the plasmasphere to outside at the time of first-hop reflection.

precipitation is plausible, since individual lightning sources have previously been found to excite paths over a longitude range extending from Siple to Halley [*Smith et al.*, 1981] and studies near L=2 within the plasmasphere have led to the conclusion that multiple precipitation regions can exist, distributed both in latitude and longitude over distances of the order of 500 km [*Carpenter et al.*, 1984].

In the case involving Siple to Palmer propagation on May 24, 1983, the inferred L shell of precipitation lay midway between the stations, or at distances of ~700 km from each, assuming precipitation near the great circle path. This location is well beyond the viewing range of most other instruments that could operate at the stations.

The new probing method should help to answer questions concerning the precipitation effects of nonducted radiation from whistler sources. If those effects are important, it should be possible to identify them by comparing the apparent locations of affected ionospheric regions with information on the ionospheric exit locations of ducted whistlers. We note that in recent polar satellite observations, electron burst precipitation was inferred to be induced by nonducted radiation from a VLF transmitter [*Imhof et al.*, 1982] and from lightning [*Voss et al.*, 1984].

The new method may be used to study precipitation associated with a variety of VLF noise phenomena, including hiss, chorus, and periodic emissions, as well as precipitation associated with other processes. It is clear from Figure 3 that both phase and amplitude of the received signals should be recorded. These will permit detailed studies of the perturbation signatures, from which information can be derived for use in modeling studies of the particle scattering process and of the ionospheric response. We note, for example, that the perturbations outside the plasmapause on July 16 decayed within about ~7s, as compared to the times of ~30 s observed at Palmer in apparent connection with precipitation within the plasmasphere. This faster decay time is not yet understood.

Important features of the new VLF probing technique in the Antarctic are selectability of observing opportunity and of frequency. Special probing experiments can be performed, for example, when particle-measuring satellites are favorably located or when perturbations are observed on signals from regular VLF sources. The probing frequency can be selected to avoid bands of natural activity, as illustrated by the data of July 16. Furthermore, the selectability of frequency permits operation in the 2–3 kHz range, where atmospheric background noise is frequently a minimum. The capability of multiple-frequency operation should permit studies of the location and extent of precipitation regions along great circle paths, based upon the frequency dependence of the wave mode structure in the waveguide.

Acknowledgments. We are grateful to the field personnel at Siple, South Pole, Halley, and Palmer stations for the conduct of the experiments, to J. Yarbrough for preparation of spectrographic records, to P. Pecen for assistance in data display, and to N. Leger for preparation of the typescript. Portions of this work were carried out during a visit by one of us (A.J.S.) to the STAR Laboratory. The work at Stanford was supported by the Division of Polar Programs of the National Science Foundation under grants for work at Palmer, South Pole, and Siple stations. The VLF project at Halley is supported by the Natural Environment Research Council.

The Editor thanks A. B. Kaiser and T. J. Rosenberg for their assistance in evaluating this paper.

REFERENCES

Armstrong, W. C., D. L. Carpenter, M. Dermedziew, R. L. Arnoldy, L. J. Cahill, T. J. Rosenberg, L. J. Lanzerotti, and S. B. Mende, A VLF source of ULF pulsations (abstract), *Eos, 64,* 815, 1983.

Arnoldy, R. L., K. Dragoon, L. J. Cahill, S. B. Mende, T. J. Rosenberg, and L. J. Lanzerotti, Detailed correlation of magnetic field and riometer observations at L=4.2 with pulsating aurora, *J. Geophys. Res., 87,* 10449, 1982.

Carpenter, D. L., and J. W. LaBelle, A study of whistlers correlated with bursts of electron precipitation near L=2, *J. Geophys. Res., 87,* 4427, 1982.

Carpenter, D. L., U. S. Inan, M. L. Trimpi, R. A. Helliwell, and J. P. Katsufrakis, Perturbations of subionospheric LF and MF signals due to whistler-induced electron precipitation bursts, *J. Geophys. Res., 89,* 9857, 1984.

Dingle, B., and D. L. Carpenter, Electron precipitation induced by VLF noise bursts at the plasmapause and detected at conjugate ground stations, *J. Geophys. Res., 86,* 4597, 1981.

Engebretson, M. J., L. J. Cahill, Jr., R. L. Arnoldy, and T. J. Rosenberg, Correlated irregular magnetic pulsations and optical emissions observed at Siple Station, Antarctica, *J. Geophys. Res., 88,* 4841, 1983.

Gail, W. B., and D. L. Carpenter, Whistler-induced suppression of VLF noise, *J. Geophys. Res., 89,* 1015, 1984.

Helliwell, R. A., J. P. Katsufrakis, and M. L. Trimpi, Whistler-induced amplitude perturbation in VLF propagation, *J. Geophys. Res., 78,* 4679, 1973.

Helliwell, R. A., S. B. Mende, J. H. Doolittle, W. C. Armstrong, and D. L. Carpenter, Correlations between λ4278 optical emissions and VLF wave events observed at $L \sim 4$ in the Antarctic, *J. Geophys. Res., 85,* 3376, 1980.

Imhof, W. L., J. B. Reagan, H. D. Voss, E. E. Gaines, D. W. Datlowe, J. Mobilia, R. A. Helliwell, U. S. Inan, and J. Katsufrakis, The modulated precipitation of radiation belt electrons by controlled signals from VLF transmitters, *Geophys. Res. Lett., 10,* 615, 1983.

Leyser, T. B., U. S. Inan, D. L. Carpenter, and M. L. Trimpi, Diurnal variation of burst precipitation effects on subionospheric VLF/LF signal propagation near L=2, *J. Geophys. Res., 89,* 9139, 1984.

Lohrey, B., and A. B. Kaiser, Whistler-induced anomalies in VLF propagation, *J. Geophys. Res., 84,* 5121, 1979.

Oguti, T., J. H. Meek, and K. Hayashi, Multiple correlation between auroral and magnetic pulsations, *J. Geophys. Res., 89,* 2295, 1984.

Paschal, E. W., and R. A. Helliwell, Phase measurements of whistler mode signals from the Siple VLF transmitter, *J. Geophys. Res., 89,* 1667, 1984.

Potemra, T. A., and T. J. Rosenberg, VLF propagation disturbances and electron precipitation at mid-latitudes, *J. Geophys. Res., 78,* 1572, 1973.

Rosenberg, T. J., R. A. Helliwell, and J. P. Katsufrakis, Electron precipitation associated with discrete very low frequency emissions, *J. Geophys. Res., 76,* 8445, 1971.

Smith, A. J., D. L. Carpenter, and M. Lester, Longitudinal variations of plasmapause radius and the propagation of VLF noise within small ($\Delta L \sim 0.5$) extensions of the plasmapause, *Geophys. Res. Lett., 8*(9), 980, 1981.

Voss, H. D., W. L. Imhof, J. Mobilia, E. E. Gaines, M. Walt, J. B. Reagan, U. S. Inan, R. A. Helliwell, D. L. Carpenter, J. P. Katsufrakis, and H. C. Chang, Lightning-induced electron precipitation, *Nature, 312,* 5996, 1984.

Westerlund, S. and F. H. Reder, VLF propagation at auroral latitudes, *J. Atmos. Terr. Phys., 35,* 1453, 1973.

D. L. Carpenter, U.S. Inan, and E. W. Paschal, STAR Laboratory, Stanford University, Stanford, CA 94305.

A. J. Smith, British Antarctic Survey (NERC), Madingley Road, Cambridge, CB3 OET, England.

(Received October 15, 1984;
revised December 17, 1984;
accepted December 18, 1984.)