JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A2, PAGES 1015–1022, FEBRUARY 1, 1984

Whistler Induced Suppression of VLF Noise

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New evidence has been found connecting whistlers with transient reductions in the amplitude of magnetospheric VLF noise bands. Until now, the only reported examples of such effects were observed during a several hour period at Siple Station, Antarctica, when bursts of particle precipitation were correlated with whistlers that suppressed a background hiss band. Data acquired at South Pole Station during 1981 showed similar suppression events on 20% of all winter days. A review of data from Siple, Byrd, Eights, and Palmer Stations in Antarctica and Roberval in Quebec, Canada, has since identified many more events. The ground signature of an event is characterized by the attenuation of an existing VLF noise band following the arrival of a whistler. The attenuation typically reaches a maximum of 3–5 dB in 5–10 s, and the noise band recovers to the pre-event amplitude 15–30 s after the whistler. The noise bands are generally mid-latitude hiss, but suppression associated with polar chorus has been seen. Regularly observed features of suppression events include multi-hop echoing of the driving whistler; confinement of the whistler echoes to the frequency band occupied by the suppressed noise; suppression during the first pass of the whistler; continuing suppression by the whistler echoes as the suppressed noise amplitude reaches a minimum and then recovers; and recovery of the noise band to the pre-event level. Event duration was found to increase with the duration of the whistler echo train. Some data suggest that this phenomenon may be a natural analog of the previously reported quiet band effect in which signals from the VLF transmitter at Siple Station were observed to attenuate portions of noise bands.

1. INTRODUCTION

Ground-based observation of VLF noise has been used for more than three decades as a primary method for studying wave and particle phenomena in the magnetosphere. Much work has focused on the magnetospheric generation of VLF noise and emissions through triggering by both natural and artificial signals. However, research by several investigators [*Brice*, 1965; *Ho*, 1973; *Helliwell and Katsufrakis*, 1974; *Raghuram*, 1977; *Raghuram et al.*, 1977*a,b*; *Helliwell et al.*, 1980] has demonstrated that these triggering signals can also suppress or attenuate previously existing VLF noise. While studies of both naturally and artificially triggered noise forms have revealed much about the way waves interact with particles in the magnetosphere, little is known about how injected waves affect the ambient wave environment. Suppression events provide a ground-based means of studying this problem.

In this paper we investigate a class of suppression effects involving the reduction in amplitude of a natural VLF noise band following the reception of a whistler. Figure 1 shows an example of two suppression events recorded in real time at South Pole Station. The unperturbed trace represents the ambient noise level in a 1–2 kHz bandpass filter. The noise band in this example was polar chorus in the range 0.3–1.5 kHz. Reception of two whistlers is indicated by positive spikes in the chart. Following both whistlers, the amplitude dropped sharply and reached a minimum of 6–8 dB below the pre-whistler level within about 10 s. Recovery to the pre-event level lasted approximately 10–15 s after the minimum.

The only previously recognized observations of suppression events similar to those in Figure 1 were discussed by *Helliwell et al.* [1980] in a paper describing one-to-one correlations between optical emissions and VLF wave phenomena at Siple Station. The noise attenuation during these events was correlated with the photometer pulses, which were assumed to result from particle precipitation induced by whistlers. Suppression was observed in one case at both Siple and its conjugate station, Roberval. The authors suggested that both the hiss reduction and particle precipitation were caused by pitch angle scattering of trapped electrons by whistlers. Our work indicates that these few occurrences are in fact part of a relatively broad class of whistler suppression activity. Whistler suppression effects were identified on 5-10% of all days for which data from Siple (Λ=61.1S, $L \sim 4.3$) and South Pole (Λ=73.8S) Stations in Antarctica were available and were seen on occasion as far equatorward as Palmer Station (Λ=48.5S, $L \sim 2.3$).

A similar effect was observed by *Raghuram et al.* [1977*b*] that involved suppression of noise bands by Siple transmitter signals. Several examples were presented in which a Siple CW signal attenuated a 50 to 200–Hz portion of a mid-latitude hiss band at frequencies directly below the transmitter frequency. This "quiet band" developed in 8–22 s and recovered 30–44 s following termination of the transmission. The authors suggested that the hiss reduction was due either to changes in the slope of the particle distribution function or to a decrease in the particle flux. A theoretical analysis of the phenomenon was done by *Cornilleau-Wehrlin and Gendrin* [1979], who proposed a process involving nonlinear trapping and detrapping of particles.

Related effects have been observed by several authors. *Brice* [1965] demonstrated that periodic emissions (emissions groups with a period equal to the whistler echo period) can be self-suppressing. *Ho* [1973] discussed triggering,

Paper number 3A1547.
0148-0227/84/003A-1547$02.00

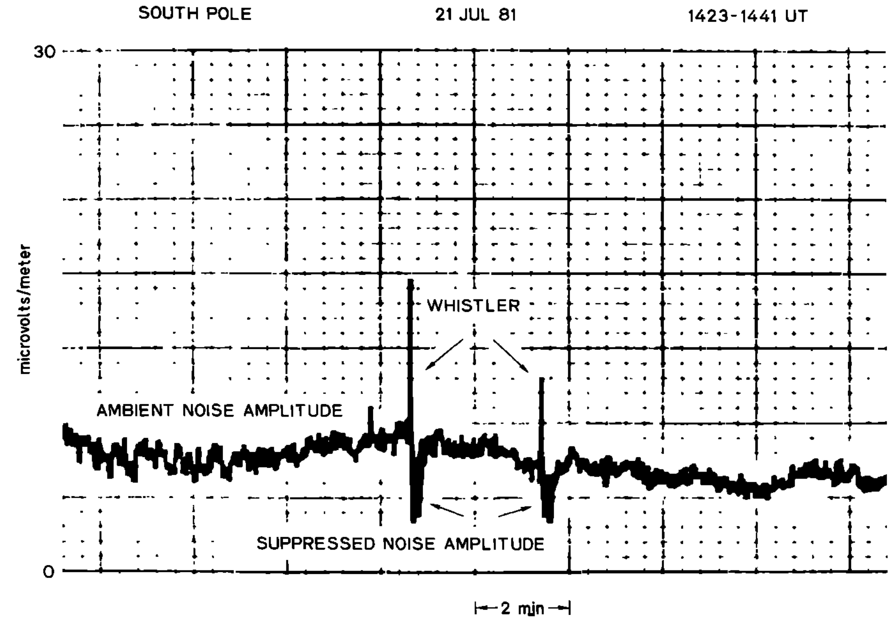

Fig. 1. Chart record from South Pole Station showing two whistler suppression events. Noise amplitude in the 1–2 kHz band is displayed versus time.

modification, and attenuation of quasi-periodic (QP) emissions (periods ~10–100 s) by whistlers. Both authors suggested that the observed effects could result from wave-induced changes in the particle population along the propagation path. Suppression of Siple transmitter signals following the arrival of echoes from previously transmitted signals at the same frequency was noted by *Raghuram et al.* [1977*a*]. Attenuation of Siple CW signals by whistlers was reported by *Helliwell and Katsufrakis* [1974] and *Raghuram* [1977]. These effects were attributed to a wave/wave interaction mechanism [*Raghuram*, 1977].

2. DATA SOURCES AND METHODS OF ANALYSIS

The data presented in this paper were taken from narrowband VLF amplitude charts and broadband tapes (~0.3–25 kHz) recorded at five Antarctic stations and at Roberval, Canada. Table 1 provides information on station locations and data set parameters. The available narrowband filter frequencies were 0.5–1 kHz, 1–2 kHz, 2–4 kHz, and 11–13 kHz, although not all filter outputs were necessarily recorded. Tape recordings followed a synoptic format of 1 min in each 15, with continuous recordings made at the discretion of the operator.

Owing to the requirement of reviewing large quantities of data, the chart records were used to identify events. When available, broadband tape records of events were analyzed for spectral information. Figure 2 shows chart segments illustrating several different signatures of whistler suppression. In each case, the impulsive increases are the amplitude traces of whistlers or whistler echoes. The initial impulse is often followed by impulses of decreasing size, representing a whistler and associated echo train. Echo trains are particularly clear in Figures 2*a* and 2*c*, while Figures 2*b* and 2*d* show very little echoing. Suppression events were identified in the chart records by the conjunction of whistler impulses of this type with subsequent reductions in the noise amplitude. Both the length of the observed reduction and the existence of similar whistler impulses not associated with any reduction suggest that the noise suppression could not be due to saturation of the linear amplifiers. In most cases, events were distinctly different from ambient noise activity. Candidate events were rejected if any ambiguities were evident.

Several limitations in the data collection process reduced the amount of data from which events could be identified. Most important of these was the interruption of natural activity recording at Siple during transmitter operation. Additional loss of data occurred because of differences in station operation and filter channel availability. Because

TABLE 1. Data Set Information and Coordinates for VLF Stations

Data Set Station	Year	Geographic Latitude Degrees	Geographic Longitude Degrees	Invariant Latitude Degrees	Recorded VLF Chart channels	No. of days Analyzed	No. of days with events
Byrd	1965	80.0S	120.0W	67.9S	0.5–1, 1–2, 2–4, 11–13 kHz	322	8
Eights	1965	75.2S	77.2W	59.5S	Comparison only	...	...
Siple	1974	75.9S	84.3W	61.1S	Comparison only	...	...
	1977				1–2, 2–4 kHz	339	21
	1978				1–2, 2–4 kHz	322	15
	1979				2–4 kHz	308	6
	1980				2–4 kHz	335	17
Roberval	1977	48.4N	72.3W	61.3N	Comparison only	...	...
Palmer	1978	64.8S	64.1W	48.5S	0.3–1, 1–2, 2–4, 7.2–8.8 kHz	245	2
	1979				0.3–1, 1–2, 2–4, 7.2–8.8 kHz	344	0
	1981				0.3–1, 1–2, 2–4, 7.2–8.8 kHz	365	0
South Pole	1981	90.0S	...	73.8S	0.5–1, 1–2, 2–4, 11–13 kHz	273	28

of these losses, any reference to long-term occurrence rates or probabilities represents a lower limit based on available data.

3. EXPERIMENTAL RESULTS

As indicated in Table 1, suppression events were detected on 5% of all analyzed days at Siple and 10% of all analyzed days at South Pole. On two occasions, events were observed at Palmer ($L \sim 2.3$). Both events followed exceptionally large magnetospheric disturbances for which Kp reached a value of 8 in the 24 hours preceding the event. The occurrence rates tended to be higher during austral winter than austral summer, possibly because of losses resulting from the increased ionospheric absorption levels during summer months. Events were seen on 33% of the June–July days at South Pole during 1981. The events at both South Pole and Siple occurred predominantly at local times corresponding to the dayside magnetosphere.

Figure 3 shows an example of a well defined suppression event observed at Siple Station. Figure 3*a* is a compressed record showing the event in the context of surrounding activity. The impulsive increases in this record represent whistlers or whistler echoes. Figure 3*b* is an expanded record of the activity near 1126 UT and Figure 3*c* is the corresponding spectral record. In Figures 3*b* and 3*c* a well-defined noise band can be seen just prior to the appearance of a whistler at 1125:42 UT. The spectral record shows evidence of strong whistler multipath propagation and some indication of emission triggering. Figure 3*b* shows that immediately following the disappearance of the whistler signal the amplitude of the noise band dropped below the pre-whistler level. The time at which this occurred is not well-defined in the record due to the masking effect of the whistler itself. The first whistler echo was detected just after 1125:44. The echo was diffuse and showed no visible multicomponent structure. The chart trace continued to decrease after the echo until an amplitude 7 dB below the unperturbed level was reached near 1125:50. The band then recovered until the pre-event level was attained around 1125:53. Recovery details are complicated by a whistler that appeared at 1125:52.

This example illustrates features that were common to most observed suppression events. The noise band is typical both in frequency range and in the hiss-like structure. Whistlers generally had multiple components and were followed by a train of diffuse echoes. The immediate attenuation of the noise band following the whistler was characteristic of suppression events as was the recovery of the noise band to the pre-whistler level. The events during any several hour period were generally similar in form; events from one period often showed marked differences from those of another period. Variations in event form are illustrated by the four event periods in Figure 2.

The noise bands generally consisted of diffuse band-limited noise, although some discrete structure was observed. The bands were typically 1–2 kHz wide in the range 1–5 kHz with edges that varied from well-defined to diffuse. Some bands had a lower limit below the equipment frequency response (300 Hz). Multiple bands were seen on occasion. Noise bands of the type shown in Figure 3 and observed in conjunction with most suppression events are generally defined as mid-latitude hiss [*Dowden*, 1971]. This hiss is characterized by a band-limited noise at frequencies of a few kilohertz. In contrast, plasmaspheric hiss usually occurs at frequencies less then 1 kHz [*Thorne et al.*, 1973], while auroral hiss tends to peak at frequencies greater than 4 kHz [*Helliwell*, 1965]. Mid-latitude hiss is also characterized by preferential amplification of whistlers in the noise band [*Dowden*, 1971] and is often accompanied by efficient whistler echoing [*Ho*, 1974; *Raghuram et al.*, 1977*b*].

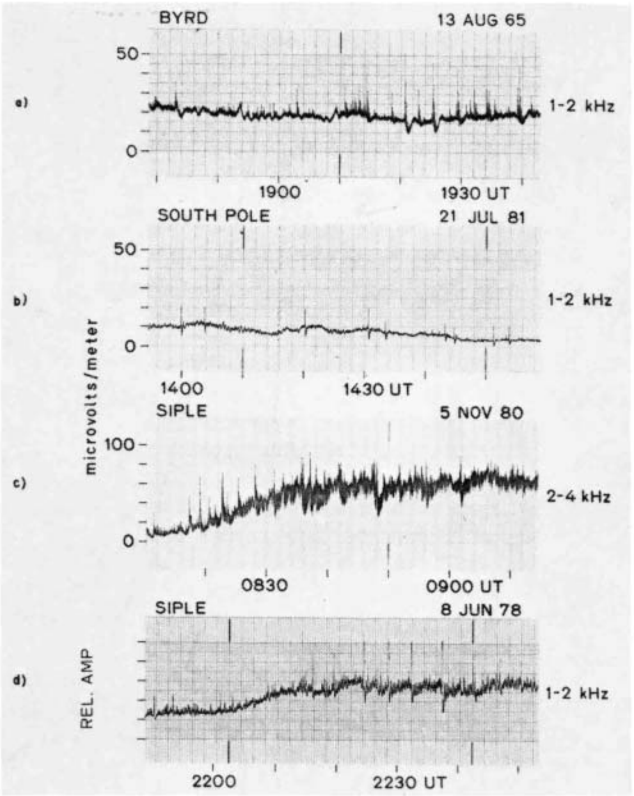

Fig. 2. Chart records showing VLF amplitude versus time during four suppression periods.

Figure 4 shows two examples of activity recorded at South Pole Station for which the background noise was polar chorus. In both cases, discrete elements between 500 Hz and 1500 Hz were superimposed on a diffuse noise band in the range 300 Hz to 900 Hz. The attenuation of the discrete elements following the whistler is evident, but it is unclear whether there was a corresponding reduction in the hiss band amplitude. It is possible that the hiss and chorus propagated on separate but nearby paths. *Dowden* [1971] discussed an example of such an effect and was able to measure the path parameters. Various spacecraft studies [*Dunckel and Helliwell*, 1969; *Russell et al.*, 1969; *Carpenter et al.*, 1969; *McPherson and Koons*, 1970] have shown a transition from diffuse noise bands to discrete elements during outbound passage through the plasmapause, indicating that both hiss and chorus bands may be generated simultaneously on closely spaced but separate L shells.

The importance of the correlation between whistler echoing and mid-latitude hiss was pointed out by *Raghuram et al.* [1977*b*] and *Ho* [1973]. Strong echoing was observed during many of the suppression events that were studied. In nearly all cases, the frequency range in which echoing occurred was the same as that of the ambient noise. The example in Figure 3 is a case of moderate echoing. Figure 5 shows two cases of strong echoing observed at Byrd and

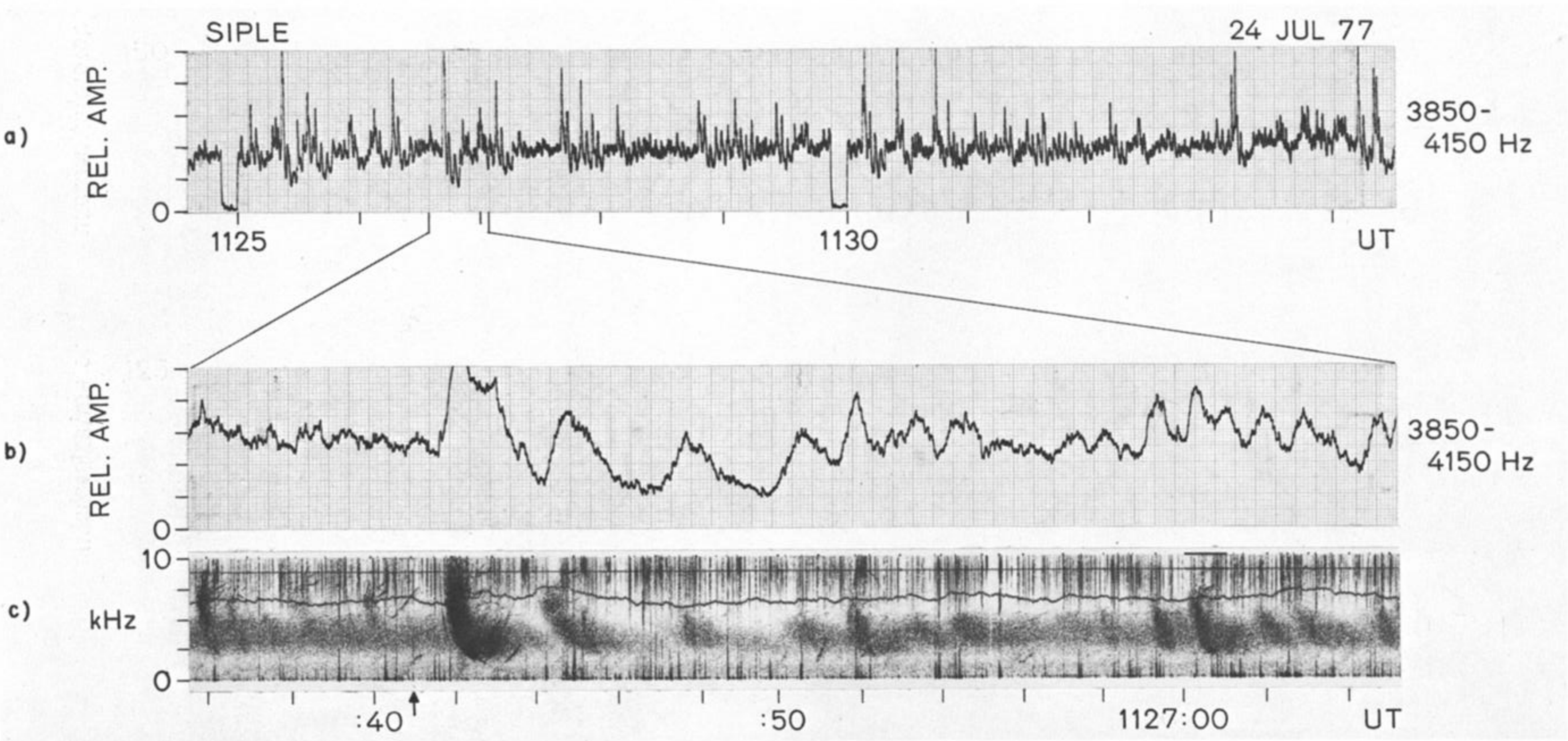

Fig. 3. Example from the suppression period noted by *Helliwell et al.* [1980] (a) Compressed 3850–4150 Hz amplitude record showing a series of suppression events over a 10-min period (integrated by using a 0.3-s time constant). (b) High resolution amplitude record showing a well-defined event. (c) Frequency-time record corresponding to (b) (integrated by using a 0.1-s time constant). The arrow indicates the causative spheric. The variable frequency line at ~6–8 kHz is the voltage controlled oscillator output from the photometer.

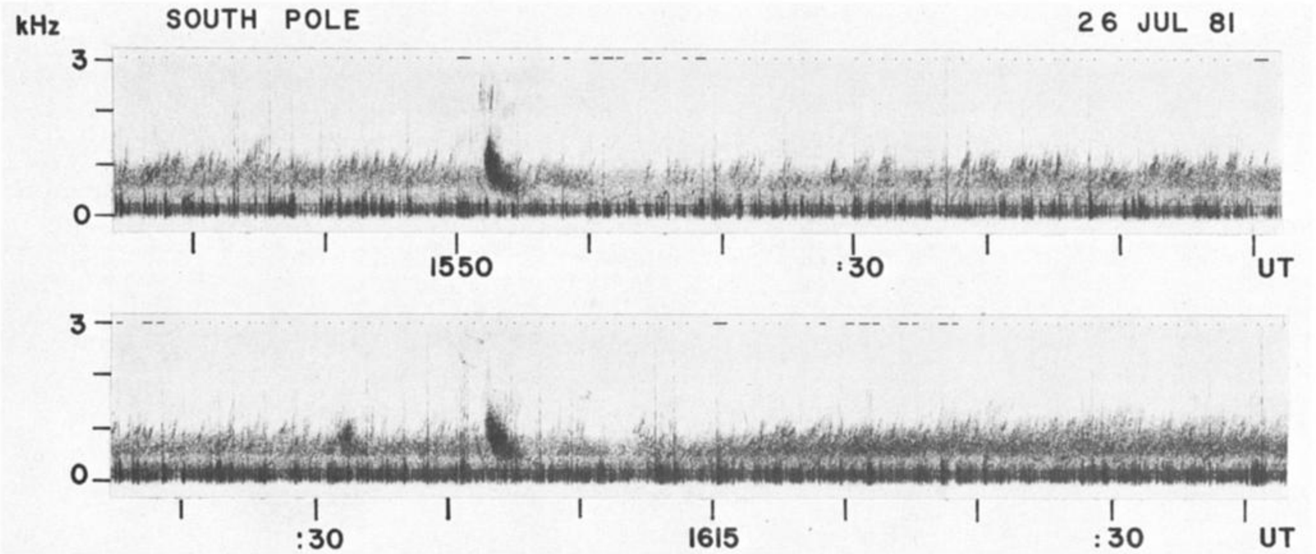

Fig. 4. Spectrograms of two events observed at South Pole showing attenuation of discrete noise in a polar chorus band.

Siple. While the one-hop signal showed that the whistler followed several paths on these days, the echoes contained little structure and maintained a constant echo period. No significant variation of the echo period was observed during any of the events studied. The suppressed noise band level did not reach a minimum until after the fifth echo in the Byrd example and the sixth echo in the Siple example. In general, strong echoing appeared to be correlated to an increase in both the time required for the noise band level to reach a minimum and the time required for the band to recover to the pre-event amplitude. For a typical event from the Siple July 24, 1977, data, 2–4 echoes were distinguishable, the minimum amplitude was reached in 5–8 s, and recovery took 3–6 s. For the Byrd August 13, 1965, events, 10–16 echoes were observed and minimum and recovery times were 35–60 s and 35–70 s.

Dispersion analysis of the examples in Figure 5 indicates that the echoing whistlers in the Byrd data propagated at $L = 5.2$ with an equatorial electron density of $N_{eq}=130$ cm^{-3} and the echoing whistlers in the Siple data propagated at $L = 4.4$ with $N_{eq}=270$ cm^{-3}. These path and density values are consistent with propagation in the outer plasmasphere. *Helliwell et al.* [1980] cited values of $L = 4.2$ and $N_{eq}=100$ cm^{-3} for the Siple July 24, 1977, events, which is interpreted as a recovery state intermediate between plasmatrough and quiet plasmasphere conditions. The parallel energy of electrons in cyclotron resonance with the noise band waves near the equator was calculated for the data in Figure 5 to be $\sim$1–2 keV for the Byrd events and $\sim$2–9 keV for the Siple events.

Determinations of onset and recovery times for the suppression effect were subject to uncertainty since most events showed suppression before the arrival of the 3-hop echo (see Figure 3) and the onset was almost always obscured by the presence of multipath whistler traces or whistler-triggered emissions. This whistler related noise often lasted for 1–2 s, a significant portion of the first echo period. Measurements of the recovery time were similarly complicated by activity fluctuations, which made determination of the recovery point difficult. The recovery time was defined as the period between the observed minimum noise level and the point where the noise band regained the level observed just prior to the whistler. This is a definition only; it may or may not be related to the time during which recovery mechanisms were acting. In Figure 3, the noise amplitude reached a minimum 8 s after the arrival of the whistler and recovered to the pre-event level about 3 s later. This recovery time was among the shortest measured for suppression events. Typically, the minimum level was attained in 5–10 s and recovery lasted 10–20 s after the minimum.

Analysis of Siple data for the May 1, 1974, period during which the Quiet Band effect was observed at Roberval [*Raghuram et al.*, 1977*b*] revealed that whistler suppression of the QB-associated noise band was occurring in addition to transmitter-induced suppression. The Quiet Band on this day involved suppression of the background noise in a $\sim$200–Hz band below the Siple transmitter frequency. The whistler suppression events were typical for whistlers with long echo trains. Using the onset and recovery criteria for the QB developed by *Raghuram et al.* [1977*b*], onset and recovery times were calculated for four whistler suppression events. Onset times were 13–15 s and recovery times were 23–35 s with mean values of 14 s and 30 s. The estimated error in these measurements is ± 3 s. These values are consistent with the *Raghuram et al.* [1977*b*] QB onset time of 8–22 s and recovery time of 30–44 s. The four events showed suppression values 3.4–3.9 dB below the pre-event level and a mean value of 3.6 dB. *Raghuram et al.* [1977*b*] measured a maximum attenuation for the QB of 6 dB below the surrounding noise.

4. DISCUSSION

Helliwell et al. [1980] showed that the whistler suppression events observed at Siple on July 24, 1977, were correlated on a one-to-one basis with precipitation events detected by a photometer. Although photometer data are not available for the other suppression events studied, the wave data for the July 24, 1977, cases are similar to those of other suppression periods. Since scattering of particles

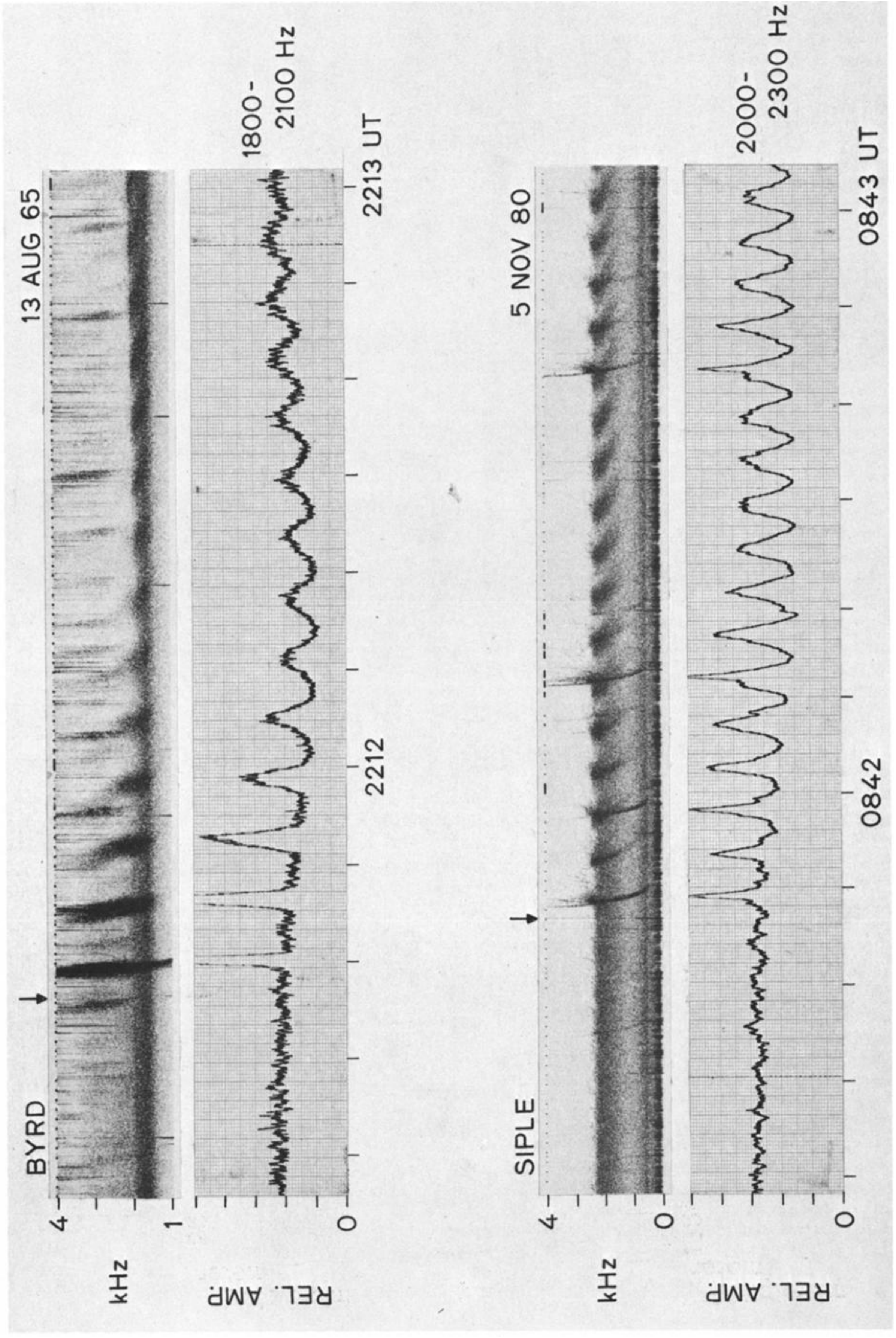

Fig. 5. Amplitude and spectral records from Byrd and Siple Stations showing long echo trains and the influence of echoes on suppression. Amplitude integration time constant is 0.3 s for the Siple record and 0.1 s for the Byrd record. Arrows indicate the causative spherics.

is considered to be a fundamental feature of magnetospheric wave/particle interactions [*Roberts*, 1966; *Inan et al.*, 1978], we suggest that measurable particle precipitation levels should regularly accompany the whistler suppression process.

The explanation offered by *Helliwell et al.* [1980] for the noise suppression and particle precipitation observed during the July 24, 1977, events (Figure 3) involves the disruption of wave amplification in the magnetospheric interaction region. Trapped electrons are scattered in pitch angle by the whistler signal and those scattered into the loss cone are observed as precipitation. The resultant reduction in the particle pitch angle anisotropy decreases the amplification efficiency for the noise band waves. This process is closely related to the process for maintenance of stable noise bands proposed by *Kennel and Petschek* [1966]. Our data is consistent with these ideas at the present level of analysis.

An alternate explanation is that particles precipitated from the equatorial interaction region produce additional ionization in the ionosphere directly below the end of the duct, resulting in attenuation of waves exiting the duct. *Helliwell et al.* [1980] found that this explanation was not supported by the observed timing relationships of an event observed at Siple and its conjugate station, Roberval. The expected (but not yet well understood) departure of the exit points of ducts in the lower ionosphere from the field lines along which the waves are ducted at higher altitudes [e.g., *Walker*, 1976] further reduces the possibility that the observed waves are attenuated by the additional ionospheric ionization that they induce.

The data indicate that suppression events for which echoing was observed tended to be longer than those with little echoing. We infer that the echoes in these cases suppressed the noise band in the same manner as the one-hop whistler. Suppression effects due to echoes would presumably decrease with time as the echo amplitudes themselves decrease. Eventually, an equilibrium condition should be reached for which the wave loss due to suppression is balanced by an increase due to the recovery mechanism. Because of the echoing, both the time required to reach the minimum amplitude and the recovery time should be lengthened. These features are consistent with the characteristics observed in the events from Byrd August 13, 1965, and Siple November 5, 1980, (Figure 5) for which strong echoing was observed.

The recovery process for suppressed noise bands has been discussed by several authors. *Brice* [1965] and *Ho* [1974] suggested that regeneration of interrupted periodic and QP emissions occurs through gradient drift replenishment of electrons scattered from the particular flux tube when the emission process is interrupted. *Kennel and Petschek* [1966] refer to an "undetermined particle source" as necessary to maintain a stably trapped particle flux. The apparent association of whistler suppression with particle precipitation suggests that replenishment of the particle population could be related to the recovery process for these events. Calculations made by *Raghuram* [1977] indicated that recovery times on the order of minutes were necessary to explain particle drift replenishment of ducts given the 4° longitudinal duct width determined from *in situ* satellite measurements [*Angerami*, 1970]. *Raghuram* [1977] suggested that shorter recovery times could be explained if noise production and suppression occurred in only a small portion of a duct. An alternate explanation is that the recovery process depends more on approximate reestablishment of the pre-event particle distribution function through a diffusive process than on particle flux replenishment.

The conjunction of the Quiet Band effect and whistler suppression in the May 1, 1974, data from Siple and Roberval suggests a correspondence between the two phenomena. The similarities in onset and recovery times further indicate that the two effects may be closely related. There are several important differences, however. The Siple CW signal that produced the Quiet Band was coherent, monochromatic, and long in comparison with the two-hop echo period. Whistlers and echoes are broadband, somewhat less coherent, and initially shorter than the two-hop period. In contrast to the Siple CW signal, they involve a decaying series of progressively more dispersed wave trains. Noise suppression for the QB occurred in a narrow (50–200 Hz) band located directly below the transmitter signal, whereas whistlers appeared to suppress the entire noise band. Onset time, recovery time, and suppression bandwidth varied with frequency for the observed QB events. Similar effects were not apparent for whistler suppression, although it is likely that the broadband nature of the whistlers made frequency distinctions undetectable. The differences between the Quiet Band effect and whistler suppression may not be fundamental and are probably attributable to differences in the driving signals.

5. CONCLUSIONS

Suppression of natural VLF noise by whistlers is a relatively common magnetospheric phenomenon, having been observed on 5-10% of the days we examined at several stations for which $L > 4$. The phenomenon can be regarded as a ground-based probe of the conditions under which a stable noise band is maintained in the magnetosphere. The following points should be considered in any theory of the suppression effect:

1. The driving whistler usually exhibits echoes that tend to be confined to the frequency band occupied by the suppressed noise.
2. Significant suppression occurs as a result of the first pass or hop of the whistler waves.
3. Successive echoes may drive the suppression process in a manner similar to that of the original whistler signal. This echo induced suppression appears to continue after the noise band minimum amplitude is reached and to therefore reduce the noise recovery rate.
4. Recovery of the noise band to the pre-event level has been observed to occur within a time as short as several seconds, although the duration of suppression appears to depend on the damping decrement of the echo train, e.g., the recovery is slower for longer echo trains. Our belief is that the recovery is intrinsically too short to be explained by gradient drift of electrons across a duct of several degrees in longitudinal width.
5. Following an event, the noise band tends to recover to its pre-event amplitude.
6. The suppressed noise bands are usually unstructured mid-latitude hiss, but suppression of structured chorus elements has also been observed.

Some events have shown evidence of occurrence along a single propagation path. This is a highly desirable circumstance in both active and passive probing experiments.

In the future, it is hoped to learn more about any suppression effects of the driving whistler echo train on itself, and to generally compare the Quiet Band and whistler suppression phenomena. At the present level of understanding, we conclude that whistler suppression and the Quiet Band effect are closely related.

Acknowledgments. We are grateful to J. Katsufrakis for management of field operations and calling our attention to the whistler suppression seen in the Quiet Band data. We thank R. Helliwell, U. Inan, and T. Bell for valuable discussions, and J. Yarbrough for assistance in data analysis. This research was supported by the Division of Polar Programs of the National Science Foundation under grants DPP 79-23171, DPP 79-24600, DPP 80-22282, and DPP 80-22540.

The Editor thanks R. Gendrin and R. L. Dowden for their assistance in evaluating this paper.

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(Received April 12, 1983;
revised June 24, 1983;
accepted August 29, 1983.)