Vol. 4, No. 5 Geophysical Research Letters May 1977

A QUIET BAND PRODUCED BY VLF TRANSMITTER SIGNALS IN THE MAGNETOSPHERE

R. Raghuram, T. F. Bell, R. A. Helliwell and J. P. Katsufrakis

Radioscience Laboratory, Stanford University, Stanford, Ca.,94305

Abstract. Signals from a VLF transmitter suppress magnetospheric mid-latitude hiss in a band up to 200 Hz wide located just below the transmitter frequency. These quiet bands take 5 to 25 s to develop and last more than 30 s after the end of transmissions. The modification of the electron velocity distribution function by the transmitter signals is a possible explanation for this new phenomenon.

Introduction

In this paper we describe an unexpected result of the magnetospheric wave-injection experiments conducted with the VLF transmitter at Siple Station, Antarctica [Helliwell and Katsufrakis,1974]. It is found that the transmitter signals suppress mid-latitude hiss in a band up to 200 Hz wide located just below the transmitter frequency. This band is referred to as the quiet band. Figure 1 schematically describes the experiments. The transmitter is denoted by T. The data shown come entirely from the receiving station at Roberval, Quebec, Canada denoted by R. The signals travel along field-aligned ducts and pass through the wave-particle interaction region near the equator. The transmitter signals are partially reflected at the base of the ionosphere and sometimes echo tens of times between the two ends of the field line (see Helliwell [1965], p. 84 for discussion on echoes).

The next section describes the characteristics of the quiet band while Section 3 outlines a possible explanation.

Characteristics of the Quiet Band

The middle panel in Fig. 2a shows a frequency-time spectrogram of a quiet band event. The top panel shows the format as transmitted from Siple Station. The bottom panel contains a sketch of the event. Though discrete 1 s pulses were transmitted at the two frequencies indicated, a continuous tone is seen at both frequencies as a result of good echoing. The transmissions occur in a band of hiss. The hiss seen here is mid-latitude hiss as opposed to plasmaspheric hiss or auroral hiss [Dowden, 1971; Gallet, 1959; Helliwell, 1965, Fig. 7-29c]. It is characterized by a periodicity in its structure equal to the two hop whistler mode travel time. It is usually accompanied by long echoing whistler trains. Plasmaspheric hiss, on the other hand, is not observed on the ground and occurs at lower frequencies. Auroral hiss, though observed on the ground, does not show the two hop periodicity and occurs at higher latitudes than mid-latitude hiss.

A quiet band can be seen beneath both transmitter frequencies in the spectrogram in Fig. 2a. The upper band is about 140 Hz wide and the lower one about 80 Hz. The triggering of rising tones by the transmitter signals is responsible for the noise enhancement above the transmitter frequency. An interesting feature is the enhancement in noise, seen as a line, just below the quiet bands. These lines in turn generate and sustain quiet bands of their own.

Figure 2b shows the same data in the form of an amplitude versus frequency plot with the transmitter frequencies shown by arrows. The quiet bands can be seen as depressions in the average noise level just below the transmitter frequencies. The ratio between the average noise amplitude at nearby frequencies and the lowest amplitude in the quiet band is about 6 db. Several peaks are visible between 4 kHz and 4.6 kHz spaced 60 Hz apart. They are induction fields picked up from power lines in the vicinity of Roberval.

The data shown in Figure 3 provide a measurement of the onset and decay times of the quiet band. The upper panel shows the transmitted format adjusted for a one-hop travel time of 1.2 s. The 30 s pulses were transmitted starting at each minute with 30 s intervals between them. The frequency was stepped up by 100 Hz after each pulse starting from 5150 Hz at 1046 UT. From 1048 UT a quiet band is seen beneath the pulses at 5350, 5450, 5550 and 5650 Hz. Table 1 gives the time taken for the quiet band to develop and the recovery time for the hiss. The recovery time is the duration of the quiet band after termination of the direct one-hop signal at Roberval. The measurements were made using spectrograms having better time resolution than Fig. 3. Amplitude versus time plots made with 38 Hz narrow-band filters centered on the quiet bands agree

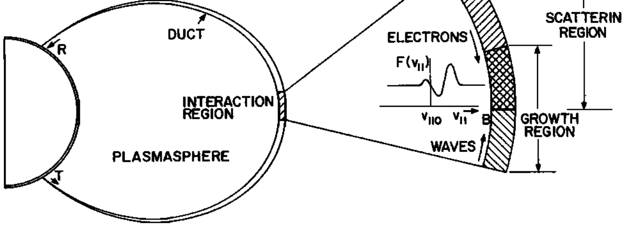

Fig. 1. Propagation of transmitter signals along field-aligned ducts. The wave-particle interaction region is near the magnetic equator.

Paper number 6L0748.

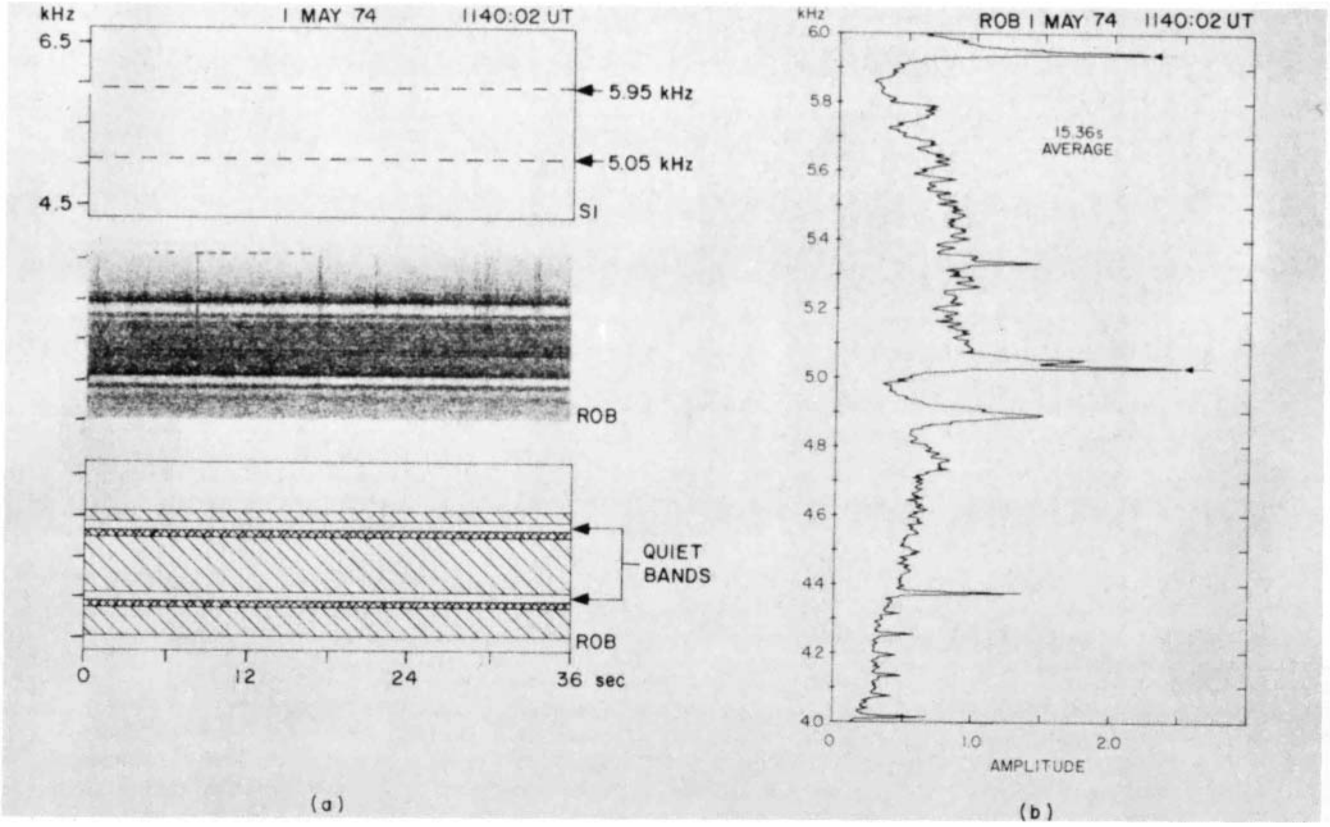

Fig. 2. The middle panel in (a) shows quiet bands in a frequency-time spectrogram. The format transmitted is shown at the top while a sketch of the received data is shown at the bottom. In (b) part of the same data is shown in an amplitude versus frequency plot.

with these measurements. Let A_1 be the amplitude before and after a quiet band event and A_2 the amplitude during the event. The beginning and end of the quiet bands were then determined by the times when the amplitude was $A_1 - 0.707 (A_1-A_2)$.

Quiet bands produced by transmitters are relatively rare. Over a 7-month period in 1974 (Apr. 1-Oct. 31) Siple transmitter signals were detected at Roberval on 34 days (Carpenter and Miller [1976] give more details on the observation of Siple transmitter signals at Roberval). Quiet bands were seen only on two of these days. A third quiet band event produced by the Omega transmitter in La Moure, North Dakota, was observed at Siple Station during the same 6-month period. Quiet bands are rare because the following conditions must be met for their existence: 1) Mid-latitude hiss must be present; 2) Frequency of transmission must be within the hiss band; 3) Transmitter signals must be amplified so that they are strong enough to suppress the hiss; 4) There must be extremely good whistler mode echoing.

On all three occasions mentioned above the quiet band occurred during a period of deep quieting in the magnetic activity. Quiet bands last from 15 minutes to an hour, at times when they are seen. It is likely that condition 4, above, is necessary for the production of the hiss rather than the quiet band itself.

On many occasions quiet bands appear just below intense narrow bands of noise of apparently natural origin. Several examples of this type of quiet band appear in Fig. 3 between 1046 and 1050 UT in the lower part of the spectrum. Quiet bands produced by sources other than the Siple transmitter are seen in the spectrogram of Fig. 4. In fact, the spectrum of the hiss is almost completely broken up into enhancements and quiet bands. Also shown are the two quiet bands pro-

TABLE 1. ONSET AND DECAY TIMES FOR THE QUIET BANDS IN FIGURE 2.

FREQ. (kHz)	TIME FOR QUIET BAND TO DEVELOP (SEC)	RECOVERY TIME FOR THE NOISE (SEC)	MAXIMUM WIDTH OF QUIET BAND (Hz)
5.35	22 ± 2	30 ± 2	53
5.45	16 ± 2	36 ± 4	73
5.55	11 ± 2	42 ± 4	80
5.65	8 ± 2	44 ± 5	80

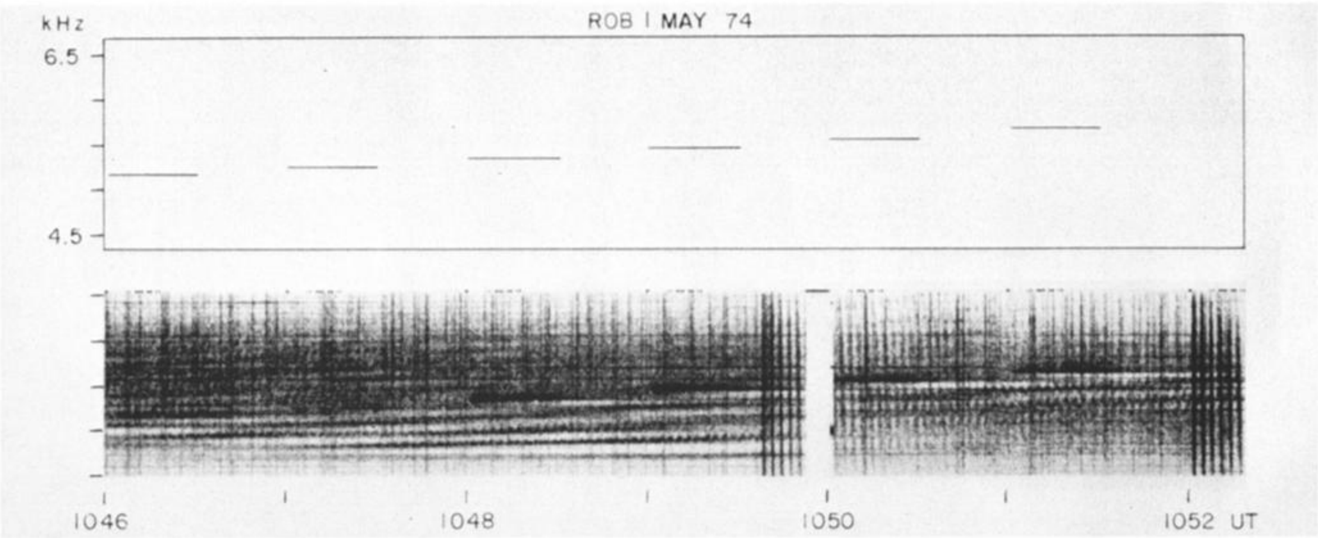

Fig. 3. The spectrogram shows onset and decay times of several quiet bands. The transmitted format is shown at the top. Successive 30 s pulses are stepped up in frequency by 100 Hz. The abrupt changes in the spectrum near 1051:00 UT are due to a change in frequency of the induction fields from the power lines near Roberval.

duced by the Siple transmitter, the transmitted format being the same as in Fig. 2. From A-scans similar to that in Fig. 2b, the width and the level of suppression of the various quiet bands were measured. The results are plotted in Fig. 4 against the amplitude of the source producing the quiet band. The source amplitudes were measured from the enhancements just above the quiet bands. The bandwidth plot is a least-squares fit to a straight line while the level of suppression plot is a least-squares fit to an exponential. Measurements corresponding to the quiet bands produced by the Siple transmitter are shown circled. Though the measurements are few, they suggest that the width of the quiet band increases more or less linearly with the amplitude of the source while the level of suppression tends to a limiting value. Figure 4 shows this limiting value to be roughly 5 db. It is actually greater because part of the unsuppressed noise is not of magnetospheric origin. The direct correlation between the source amplitude and the width and level of suppression is further evidence that quiet bands are not random noise minima in spectra.

Discussion

It is well known that VLF waves and energetic particles interact in the earth's magnetosphere. The amplification of transmitter signals, triggering of emissions, generation of hiss and related effects described here result from wave-particle interaction. As indicated in Fig. 1, the interaction is believed to occur near the magnetic equator. While the details of the interaction are not completely known, it is generally accepted that the interaction depends on doppler shifted cyclotron resonance between the waves and the electrons.

Cyclotron resonance is defined by the relation $\omega_H = \omega + kv_\parallel$, where ω_H = electron gyrofrequency, ω = wave frequency, k = wave number, $v_\parallel$ = electron parallel velocity (opposite to wave velocity). With the aid of this expression and Fig. 1, we can formulate a qualitative explanation of the quiet band. We assume that both the transmitter signal and the hiss are amplified in a region roughly centered on the equator [Helliwell, 1967]. As the amplified transmitter signal leaves the equator it scatters electrons that are close to resonance on the upstream side of the equator. As distance from the equator increases, the scattering becomes less since each electron spends less time near resonance [Helliwell, 1967]. As the perturbed electrons travel to the equator ω_H decreases, causing the resonant frequency corresponding to the modified part of the distribution to fall. Assuming that the hiss amplitude is reduced over some part of the frequency spectrum corresponding to this perturbation, there will be a gap, or quiet band below the transmitter frequency. The reduction in hiss amplitude could be produced either by changes in the slope of the distribution function or by reductions in absolute flux in the relevant part of the distribution function. For the conditions relevant to Fig. 2, ($L = 3.5$, $f = 5.9$ kHz, width of quiet band ≈200 Hz) and assuming typical magnetospheric parameters and an equatorial pitch angle of 45°, the perturbation would have to begin at a distance of 1265 km upstream from the equator. The 5 to 25 s onset time for the quiet band implies that this modification requires several electron bounce periods to become fully developed. While the quiet band itself has been observed only in the presence of hiss the modification of the velocity distribution will likely be produced anytime there is a strong coherent wave.

If the explanation outlined above is right, then the quiet band gives an indirect estimate of the perturbations in the velocity distribution function. This method of estimation is particularly convenient as it is based only on ground observations. While phenomena related to particle precipitation [Rosenberg et al., 1971; Helliwell et al., 1973] give information only on particles in or near the loss cone, no such re-

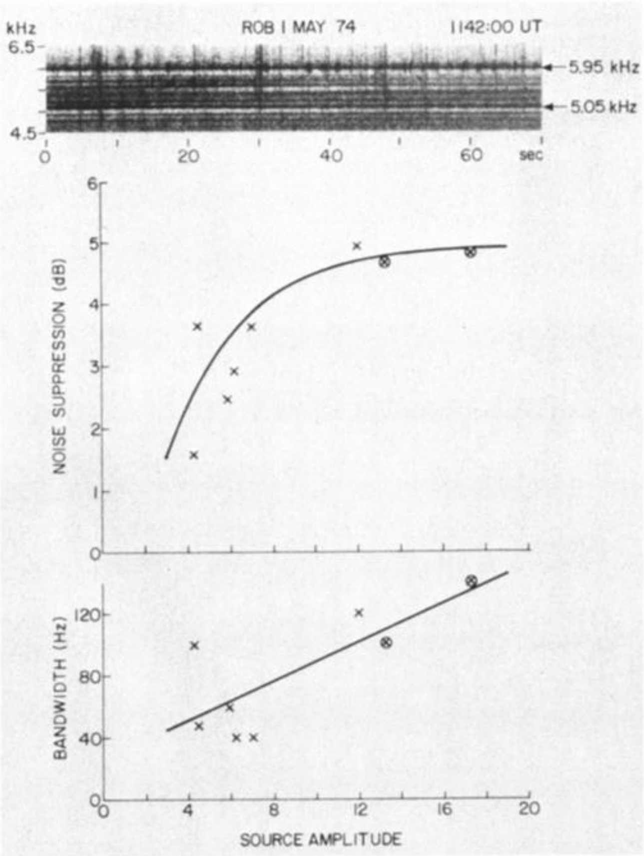

Fig. 4. Spectrogram showing quiet bands produced by sources other than the transmitter. The width and level of suppression of the quiet bands are plotted against the amplitude of the source. The amplitude scale has arbitrary units.

striction applies to the quiet band. Of course, the above explanation is speculative and requires further investigation. However, we can expect that the correct explanation will lead to a better understanding of the wave-particle interaction process. Quantities such as the bandwidth, onset time, recovery time and level of suppression of the quiet band should lead to the estimation of important magnetospheric parameters, if properly interpreted.

Acknowledgements. This work was supported in part by the Division of Polar Programs of the National Science Foundation under grant OPP-04093, in part by the Atmospheric Sciences Section of the National Science Foundation under grant DES75-07707, and in part by the Office of Naval Research under contract number N00014-76-C-0689.

References

Carpenter, D. L. and T. R. Miller, Ducted magnetospheric propagation of signals from the Siple, Antarctica VLF transmitter, J. Geophys. Res., 81, 2692, 1976.

Dowden, R. L., Distinctions between mid-latitude VLF hiss and discrete emissions, Plant. Space Sci., 19, 374, 1971.

Gallet, R. M., The Very Low Frequency emissions generated in the earth's exosphere, Proc. IRE, 47, 211, 1959.

Helliwell, R. A., Whistlers and Related Ionospheric Phenomena, Stanford Press, Stanford, Ca., 1965.

Helliwell, R. A., A theory of discrete VLF emissions in the magnetosphere, J. Geophys. Res., 72, 4773, 1967.

Helliwell, R. A. and J. P. Katsufrakis, VLF wave injection into the magnetosphere from Siple Station, Antarctica, J. Geophys. Res., 79, 2511, 1974.

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

Nunn, D., A self-consistent theory of triggered VLF emissions, Plant. Space Sci., 22, 349, 1974.

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.

(Received December 23, 1976;
revised February 28, 1977;
accepted March 22, 1977.)