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Observations of the VLF quiet band phenomenon

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Abstract. In 1979, VLF receivers were operated near Roberval, Canada, by a team from the Japanese Institute of Space and Astronautical Science. Data obtained from this experiment on July 23 near 12.16 UT show one hop signals at just below 3 kHz, originating from the VLF transmitter located at Siple Station, Antarctica. On the low-frequency side of the Siple signals, a "quiet band" of background noise suppression is visible, ~ 95 Hz in width. The time taken for the effect to develop is between 5 and 10 s and the recovery time of the noise is $\gtrsim 20$ s. The level of suppression is ~ 3 dB. The important aspect of these data is that, although growth is enhanced above the frequency of the Siple signals, on the lower border of the quiet band little or no enhancement is observed, in contrast to some theoretical models. These data are not of sufficient duration or simplicity to provide a decisive test of recent quiet band theories.

Key words: VLF waves – Quiet band – Siple transmitter – Wave-particle interaction

Introduction

The quiet band phenomenon is observed below the frequency of VLF transmitter signals propagating in the magnetosphere and develops as a band of noise suppression that can be up to 200 Hz in width [Raghuram et al., 1977, henceforth (1)]. The unexpected discovery of the quiet band reported in (1) was made during VLF wave injection experiments conducted along the Siple/Roberval meridian (Helliwell and Katsufrakis, 1974). In these experiments signals from the VLF transmitter located at Siple Station, Antarctica, may enter the magnetosphere and be guided to the northern hemisphere in ducts of enhanced ionisation which are aligned parallel to the geomagnetic field. This guidance sometimes produces detectable 'one hop' Siple signals in the conjugate region near Roberval, Canada. An additional magnetospheric response in the form of wave growth or suppression is often observed, along with the transmitter signal itself (Helliwell and Katsufrakis, 1974).

The results described in (1) and in the report by Raghuram (1977) demonstrate that the type of noise suppressed within the frequency range of the quiet band is broadband midlatitude hiss (Dowden, 1971) and that the level of suppression can be as much as 6 dB for transmitter frequencies near 5 kHz. The quiet bands were rarely observed and required conditions of good whistler-mode echoing between hemispheres. The suppression took between 5 and 25 s to develop and could last up to 1 min after the end of transmissions. Above the transmitter frequency, rapidly developing enhancements were detected due to the triggering of rising tones by the transmitter signal. On the low-frequency border of the quiet band, noise enhancements were observed to develop over a long period (~ 20 min) and seemed to be part of the hiss band itself. Secondary quiet bands could be produced below the enhanced lower border.

The quiet band events reported in (1) occurred during deep quietening in magnetic activity over a time interval of a few hours. The level of noise suppression tended to a limiting value as the amplitude of the source signal increased, whereas the frequency width of the quiet band increased roughly linearly with the source amplitude.

Earlier theoretical work (e.g. Helliwell, 1967; Das, 1978; Ashour-Abdalla, 1972; Bud'ko et al., 1972; Roux and Pellat, 1976) investigated the interaction between monochromatic VLF signals and the energetic electron distribution within the magnetosphere, mainly with a view to explaining the triggered emission phenomenon (Helliwell, 1965). Little emphasis was placed on the investigation of suppression effects. A review of some of these works, which proposes, in particular, that the quasilinear approach is inadequate for a description of the quiet band phenomenon, can be found in Cornilleau-Wehrlin and Gendrin (1979).

The discovery of the VLF quiet band phenomenon stimulated several more recent theoretical studies. Raghuram (1977) presented numerical simulation results which demonstrated that monochromatic VLF signals of large enough amplitude could alter the distribution function of energetic magnetospheric electrons, and so be responsible for the suppression below the transmitter frequency. Cornilleau-Wehrlin and Gendrin (1979) used the formalism of Roux and Pellat (1976) to present a detailed theoretical model of the phenomenon. They considered the competition between the phase trapping effects of the wave and the detrapping effects caused by the inhomogeneity of the geomagnetic field. Basically, their model relies on the reduction in particle number (caused by wave trapping) within a small range of equatorial parallel velocities corresponding to frequencies below that of the transmitter. This depletion leads to reduced growth rates. The predicted quiet band width

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*Present address: Department of Oceanography, Marine Science Laboratories, Menai Bridge, Gwynedd, LL59 5EY, United Kingdom should increase with frequency and depend on B_w^2, where B_w is the coherent wave amplitude. A strong noise enhancement was predicted at the low-frequency edge of the quiet band, but no enhancement above the transmitter frequency.

Matthews et al. (1984) used a different analytical approach. Their work was an attempt to explain computer simulation results which showed how the electron distribution becomes distorted in the presence of a coherent VLF signal. The nature and size of the distortion was found to be critically dependent on gradients in the electron distribution function with respect to parallel velocity. Matthews et al. (1984) showed that in their case the trapping-induced reduction in the number of electrons near the resonant velocity was small. They showed that changes in gradient in the electron distribution with respect to parallel velocity might account for quiet band generation. In their model a weak noise enhancement was predicted on the low-frequency edge of the quiet band, and a strong enhancement at frequencies just above the transmitter frequency. The quiet band width was predicted to vary as the square root of B_w.

In order to help resolve some of these conflicting theoretical predictions it is useful to study the experimental data in more detail. As the total number of quiet band events detected so far is small, it is important to make full use of the available data. In the present work, new observations of the quiet band are presented which basically confirm the properties reported by Raghuram et al. (1977), although, as we shall see, several factors prevent a straightforward comparison. Here we study the initial development of the quiet band in some detail. We concentrate, in particular, on how the distribution of wave energy with frequency is influenced by the arrival of the coherent signal in the interaction region. These changes can be clearly determined from the data and serve as a basis for comparison with theoretical predictions.

Observations

Between July 10 and August 10, 1979, a team from the Institute of Space and Astronautical Science in Tokyo, Japan, conducted a campaign to obtain a contour map of the field intensity of Siple transmitter signals received in the conjugate region in the northern hemisphere (Tsuruda et al., 1982). Twelve identical crossed loop VLF receivers were operated at quiet locations in the Roberval region. Data from the low-latitude station 'G' (Tsuruda et al., 1982; Machida and Tsuruda, 1984) at $L=4.15$ are presented here.

On 23 July 1979, between 1216.00 UT and 1217.00 UT, quiet bands were observed at station G below three groups of one hop Siple pulses, each of total duration 10 s. The first of these groups is labelled '*a*' in Fig. 1. The transmitted format of these signals is not obvious from the spectrogram, but consists of four 2-s pulses at the central frequency of 2,710 Hz, each of which is followed by two shorter pulses having progressively longer duration as the transmission proceeds. These shorter pulses are offset from the central frequency by +300 Hz and −300 Hz respectively. Initially they are 100 ms in duration, but reach 400 ms by the end of the transmission block. Hence the total duration of each transmitted group is 10 s. (D. Carpenter, personal communication). The other two groups are clearly visible at later times in the record, centred on the same frequency. Intense enhancements in noise are visible above the central frequency – that above the second signal group is labelled '*b*' in Fig. 1. The enhancements are made up of some discrete tones near the central frequency and a diffuse component of some several hundred Hz bandwidth. Discrete structure was also observed on the upper-frequency side in the events described in (1), although the presence of a diffuse component was not reported. The intense vertical lines in Fig. 1 are caused by local sferic activity.

Quiet bands are visible below each of the signal groups starting from '*a*', but the effect is best defined after the termination of the third group. This quiet band is labelled '*c*'. The time taken for the suppression to develop is difficult to see in the spectrograms, but detailed spectral analysis shows that it probably lies between 5 s and 10 s. The noise recovery time is $\gtrsim 20$ s. In (1), at transmitter frequencies near 5.5 kHz, recovery times for the noise were ~ 30 s, with faster recovery at lower frequencies. This seems consistent with our results. Assuming comparable conditions and extrapolating the quiet band development times given in (1) for transmitter signals near 3 kHz leads to an expected development time which is much longer than the 5–10 s observed here. Two main factors could account for this difference. At the time of observation there was evidence of magnetospheric line radiation activity and of remnant echoes from preceding transmissions (D. Carpenter, personal communication), both of which could influence the onset time.

The transmitter pulses of 1 s duration give rise to con-

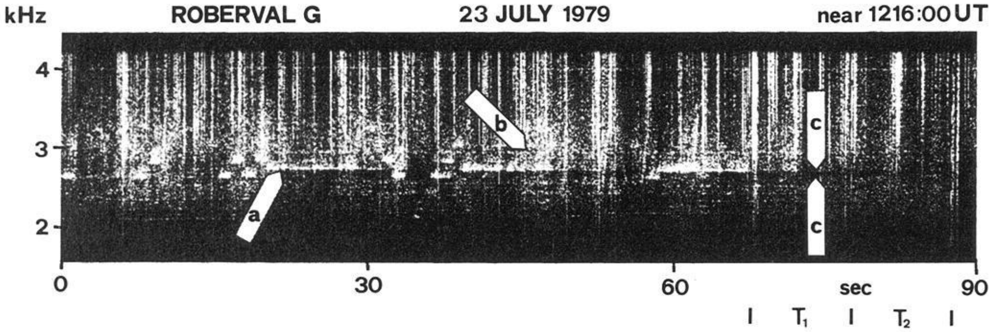

Fig. 1. The dynamic spectrograms of the three Siple VLF transmitter signal groups considered are shown, with received signals in white. The central frequency of the first group is labelled '*a*'. Noise enhancement appear above the central frequency of each group, with that for the second group labelled '*b*'. Quiet band type suppression develops below the central frequencies, and '*c*' marks the quiet band associated with the third group. The intense vertical lines are caused by sferic activity. Periods T_1 and T_2 are analysed in Fig. 2

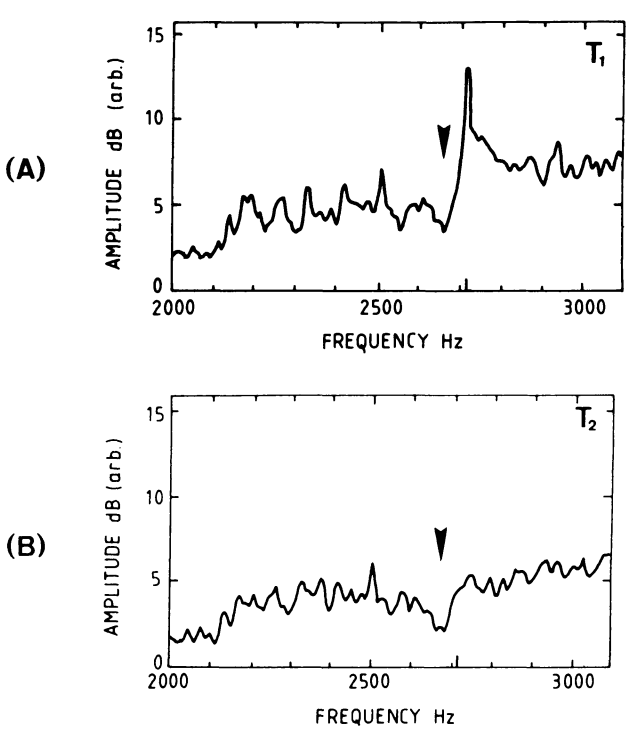

Fig. 2A, B. Amplitude/frequency plots of the 10-s data periods T_1 and T_2 shown in Fig. 1. In **A** the intense peak corresponds to the central Siple transmitter frequency. Below this peak a quiet band of noise suppression has formed (marked by *an arrow*). In **B** the quiet band is still visible, although no one-hop transmitter signal is present

siderable diffuse and discrete wave growth on their upper-frequency sides, but no quiet bands. This effect is clearly visible just before the long group '*a*'. Such growth stimulation is almost coincident with the arrival of the one hop signal, whereas the quiet bands take 5–10 s develop. Some discussion of the nature of the noise enhancement on the upper-frequency side is given by Raghuram (1977). In addition, a study of diffuse noise generation by coherent signals propagating in stable (i.e. noise-free) plasmas has been made by the author (Matthews, 1985). The details of this work are relevant to the present data, but here a bandwidth limit for the triggered hiss cannot be calculated since the plasma is already unstable. Rather, changes in the shape of the electron distribution function could act to limit the emission width.

Two time periods (labelled T_1 *and* T_2 in Fig. 1) have been analysed in greater detail. In Fig. 2A, an amplitude/frequency plot of the period T_1 is presented. Here the wave amplitude is averaged over the 10 s following the termination of the last central Siple pulse. The large peak occurs at the central transmitter frequency of 2,710 Hz. Some contribution from the one hop transmitter signal (and previous echoes) is probably present here since it is difficult to determine the exact termination time. On the low-frequency edge of the central transmitter frequency the quiet band of suppression is visible (marked with an arrow) and extends down to a frequency of 2,615 Hz, giving a quiet band width of ~95 Hz. The short 400 ms pulses transmitted at the end of the format blocks lie well outside this frequency band. These short-duration signals do not seem to play an important role in determining the properties of the quiet bands.

On the low-frequency border of the quiet band, the noise level is close to the unperturbed amplitude and there is no pronounced noise enhancement. Below the lower border the noise level is again depressed. In (1) this effect was described as a 'secondary quiet band'. It may lead to the generation of magnetospheric line arrays such as power line harmonic radiation (Helliwell et al., 1975; Matthews and Yearby, 1981).

Above the central transmitter frequency the overall level of wave activity is intensified, especially immediately above this frequency. In the discussion of Fig. 1 this was identified as being due to discrete rising tones and to an intensification of the general hiss level which is lower prior to the arrival of the transmitted signals.

In Fig. 2B, the amplitude/frequency plot represents an average over the 10-s period marked as T_2 in Fig. 1. The intense peak corresponding to the central transmitter frequency (2,710 Hz) which was visible in Fig. 2A is now absent. A quiet band of suppression is still present (marked with an arrow) – its width is 95 Hz and the level of suppression is 3 dB. Both of these values are comparable with the observations reported in (1).

On the low-frequency border of the quiet band shown in Fig. 2b the noise is near the background level as in Fig. 2a. Here too, a strong noise enhancement is not observed on the lower border. The secondary quiet band is barely visible in this plot. Above the central transmitter frequency the noise level is comparable to the pre-transmission values.

Discussion

The limited amount of data presented in this paper confirm, in a general way, the results reported in (1) and by Raghuram (1977). In particular, in the initial stages of quiet band formation studied here, intense enhancement at the lower border of the quiet band were not observed. This agrees with the detailed observations presented by Raghuram (1977) which show that the lower border enhancement develops slowly (i.e. over a period of some 20 min). On the other hand, growth enhancements above the transmitter frequency developed rapidly in both these data and in those of (1). Quiet band widths and levels of suppresion are similar in both studies. One additional feature reported here is the enhancement in diffuse noise level (in addition to discrete emissions) above the transmitter frequency. Because of the possible influence of magnetospheric line radiation, previous transmitter echoes and a complex transmitter format, the comparison between these observations and those of (1) is not a direct one.

Theories of the coherent whistler-mode wave/energetic electron interaction can be applied, with various degrees of success, to explain the data presented here. For example, the quasilinear theory of Welti et al. (1973) predicts absorption above and below the transmitter frequency. This is clearly at odds with the present data and with those reported in (1). However, the model of Das (1968) comes quite close to the situation observed here, except that a large growth rate is predicted both above and below the transmitter frequency (rather than a weak or zero enhancement below the transmitter frequency). The reason for this is probably that Das (1968) did not consider the effect of trapping at points away from the equator.

In Ashour-Abdalla (1972), a scheme for computing pitch angle diffusion coefficients was derived to study the effect of narrow band VLF signals on the electron distribution function. Trapping of particles by the waves was not considered. In the long time limit, a strong peak in growth above, and offset from, the transmitted pulse was predicted. On the low-frequency side the model gave a region of suppressed growth bordered by a weak enhancement. These predictions are similar to the observations reported here. In particular, the width in frequency covered by the suppression was about 96 Hz, although this value was obtained for a 10-pT wave amplitude, a wave frequency of 16 kHz and L value of 3 (rather different parameters to those relevant here). The lower border enhancement was shown to develop at later times ($t \sim 500$ s), which fits the observed behaviour. In the long time limit, Ashour-Abdalla's work seems to show a suppressed band with a frequency width independent of wave amplitude, which is at odds with Raghuram's data. However, the data reported here do not indicate a strong dependence of the time averaged Δf on B (see later). In addition, a gradual shift in the peak growth to higher frequencies is predicted – this is not observed in connection with the present data, and is more relevant to the situation of discrete triggered emission generation. Further, Ashour-Abdalla's theory requires a long time ($t \sim 500$ s) for the growth of wave energy above the transmitted frequency to develop. As described in this report, growth enhancements on the upper-frequency side develop more rapidly than this.

Cornilleau-Wehrlin and Gendrin (1979) predicted a strong noise enhancement at the lower border of the quiet band but no enhancement above the transmitter frequency. As far as the lower border enhancement is concerned, this model could possibly describe the situation in which a long transmitter pulse (e.g. of length 10 min) produces quiet bands. This is because the lower border enhancement is established slowly. However, it does not seem appropriate to the early stages of quiet band development studied here. Matthews et al. (1984) predicted a relatively weak lower border enhancement and a strong enhancement just above the transmitter frequency. In their results (see Fig. 8b of Matthews et al. 1984), a secondary quiet band effect may also be visible. This model fits the present observations well.

The important question of whether the quiet band width varies with the coherent wave amplitude (B_w) as B_w^2 (Cornilleau-Wehrlin and Gendrin, 1979) or as the square root of B_w (Matthews et al., 1984) cannot really be investigated with these limited data. However, for the three quiet bands, averaged widths over the duration of the suppression are 100 Hz, 100 Hz and 120 Hz, respectively, and the corresponding amplitudes are 7.7, 5.2 and 9.3 in arbitrary units. There is, therefore, a broader range of relative variation inamplitude than there is in frequency, which militates against a B_w^2 type of dependence. This result is not decisive since signal amplitudes could vary with the mixing of returning two hop transmitter echoes.

For theories employing the concept of particle trapping by the coherent signal it is important to consider what happens when the transmitted wave is switched off and the wave-induced phase-ordering of particles is consequently terminated. The quiet band might, on first reflection, be assumed to rapidly decay, rather than to fade slowly over a time scale of $\gtrsim 20$ s. However, if wave growth is to pick up again within the frequency range previously occupied by the quiet band, the distribution function must be restored to something like its pre-transmission configuration, and the randomization introduced by the phase mixing process and wave-induced pitch angle diffusion overcome. One way for this to take place is for fresh particles to be provided by the process of pitch angle diffusion, as suggested by Cornilleau-Wehrlin and Gendrin. The strong hiss band, which is always present on the lower-frequency side in the data of Fig. 1, should lead to a smoothing of the wave-induced perturbation by pitch angle diffusion on an approximate time scale (Matthews, 1985)

$$\Delta t \sim \frac{1}{2\Omega}\left(\frac{V_s B}{V_\perp B_h}\right)^2$$

where $V_s = 2\omega_t/k$ and $\omega_t = \sqrt{k v_\perp e B_w/m}$. A value of $v_\perp$ can be obtained by using the whistler-mode dispersion relation together with the gyroresonance relation, and assuming $v_\perp = v_\parallel$. This gives $v_\perp = 4 \times 10^7$ m s^{-1} at $L=4$ and a wave frequency of 3 kHz. Estimating $B_w \sim 5$ pT and, from Fig. 2a a corresponding value of $B_h \sim 1$ pT for the r.m.s. hiss wave field, we obtain $\Delta t = 73$ s, which is reasonable. Other source mechanisms, such as azimuthal particle drift or radial diffusion would restore the distribution function over much longer time scales.

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