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VLF WAVE INJECTION EXPERIMENTS FROM SIPLE STATION, ANTARCTICA

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Abstract: The background of VLF wave-particle experiments from Siple Station, Antarctica, including wave-induced precipitation is briefly reviewed. Single frequency ducted signals that exceed a certain 'threshold' intensity are observed at the conjugate point (Roberval, Quebec) to be amplified 30–50 dB, with temporal growth rates of 30–200 dB/s. Following saturation, variable frequency emissions are triggered. When a second signal is added to the first, with a frequency spacing $Df<100$ Hz, signal growth is reduced and sidebands are generated at frequencies separated from the carriers by integer multiples (up to seven) of Df. The sidebands are attributed to short emissions triggered by the beats between the two input carriers. Mid-latitude magnetospheric hiss is crudely simulated by a sequence of 10 ms pulses whose frequencies are chosen randomly within a 400 Hz band. Results show that certain combinations of 10 ms pulses link together to form chorus-like elements, suggesting a common origin for hiss and chorus. Under conditions of strong echoing, emissions may form into lines; a recent example, started by the Siple Station transmitter, exhibits interline spacings of about 45 Hz. These lines, called magnetospheric line radiation (MLR), vary slowly in frequency and show no simple connection to the harmonics of the Canadian power grid. Interline suppression may play a role in determining the spacing of MLR lines and the absence of discrete triggered emissions.

1. Introduction

One of the best known conjugate phenomena is the echoing whistler-mode signal. An electromagnetic impulse from a lightning flash or a VLF transmitter enters the ionosphere and becomes trapped in one or more field aligned enhancements of ionization, called ducts, as depicted in Fig. 1. As the signal propagates the dispersive property of the anisotropic plasma causes the group velocity to vary with frequency. In the case of the lightning-impulse, the lowest frequencies travel more slowly than higher frequencies, causing the source impulse to be transformed into a musical tone of descending pitch upon arrival at the conjugate point in the opposite hemisphere. A whistler may echo many times between conjugate points before disappearing into the background noise (HELLIWELL, 1965). Whistler-mode propagation is explained in terms of cold plasma theory and provides the basis for a quantitative technique of remote sensing of magnetospheric plasmas (PARK and CARPENTER, 1978).

Closely allied with whistlers are VLF emissions which travel along the same paths. These include chorus and hiss, and a variety of discrete emissions which may be triggered

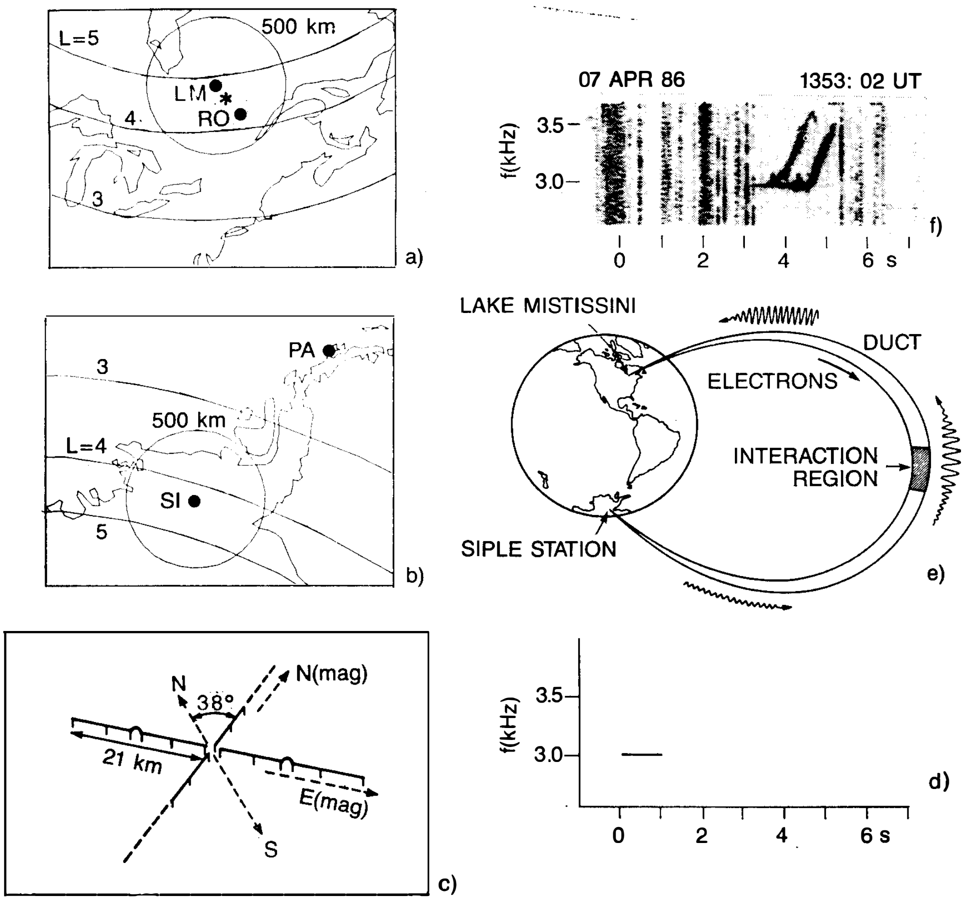

Fig. 1. Siple/Lake Mistissini experiment plan. (a) Map showing the new station, Lake Mistissini (LM), previous station, Roberval (RO), and estimated Siple Station conjugate point (*) for 1986 (STASSINOPOULOS et al., 1984). (b) Map of Antarctic Peninsula, showing Siple Station (SI) and Palmer Station (PA). (c) Crossed dipole antenna at Siple, with planned extensions shown as dashed lines. (d) f-t diagram of 1-s pulse at 3 kHz. (e) Diagram of duct propagation path from Siple to conjugate region, showing wave growth near equatorial plane. (f) f-t diagram of two one-hop amplified signals with associated emissions that propagated to LM in two ducts that were excited by the 1-s pulse of (d). The time delays are 2.7 and 3.3 s respectively.

by whistlers, ground-based transmitters (*e.g.*, Fig. 1) or other emissions. One of the remarkable features of the conjugate point echoing of wave trains is the fact that on occasion they show virtually no decrease in amplitude with time. This requires amplification along the path to restore losses occurring at the ends of the path. Such amplified and echoing VLF emissions are called periodic emissions (HELLIWELL, 1965). They can be started by whistlers or other VLF signals or may occur spontaneously within the plasma. They are thought to be an important cause of precipitation of energetic electrons in the enegry range from 0.5 keV to several hundred keV (INAN *et al.*, 1982).

One especially interesting type of VLF emission is magnetospheric line radiation (MLR), which is often associated with harmonics of the power grids near the path end points. However, the connection between the line radiation and the power lines is not well understood. It has been proposed that power line radiation is amplified in the same way as narrowband signals from a ground-based transmitter and that these lines may exercise some modifying effect on both VLF emissions and the amplification of whistlers (HELLIWELL *et al.*, 1975).

Experiments using the Siple Station VLF transmitter have revealed surprising features of the interaction between single-frequency waves and particles and between multiple signal components that are closely spaced in frequency. It is the purpose of this paper to review the properties of coherent wave amplification and related nonlinear interactions in the magnetosphere and to show how these properties may be connected to the characteristics of natural noise, including MLR.

In the first experiment the response of the magnetosphere to injected coherent waves of single frequency is measured. The second experiment concerns the response to a pair of closely-spaced frequencies; the results show suppression and sideband generation. The next step in complexity is to inject simulated noise bands. Initial results from these noise simulation experiments place important constraints on models of wave-wave interaction in the magnetosphere.

Following the review of experiments the connection between chorus and hiss will be discussed. Conclusions will note new hypotheses that arise from the experimental results. The need for more work in the areas of experiment and modeling is emphasized.

2. Single Frequency Response

In order to stimulate phenomena that are characteristic of so-called "single frequency injection" the bandwidth of the signal must be appreciably less than 10 Hz. Step function CW waves transmitted either as slowly varying frequency ramps or constant frequency pulses are used to study growth, saturation, and triggering. An example is shown in Fig. 2 where amplitude, phase, and dynamic frequency spectra are represented as functions of time (PASCHAL and HELLIWELL, 1984). The primary characteristic of single frequency response is temporal growth of the order of 30 dB. Growth is approximately exponential with time, up to saturation, and is nearly always accompanied by advancing phase of the output signal. Following saturation the phase usually continues to advance until a sharp transient occurs in the interaction causing the triggering of an emission (see Fig. 2 at 33.8 s). The emission usually appears at about the saturation amplitude while its frequency advances relatively rapidly, with the emission acquiring an independent existence as a self-excited oscillation. The frequency of an emission may vary in complicated ways after triggering occurs. Upon approaching the frequency of another injected signal a free running emission may become entrained by that signal (HELLIWELL and KATSUFRAKIS, 1978). One of the most interesting effects connected with the response to a single frequency pulse is the generation of a band-limited impulse which appears usually just before the triggering of a riser or at the end of the applied pulse (see Fig. 2). Such pulses may have bandwidths as high as 500 Hz.

Single frequency temporal growth does not occur unless the input signal exceeds a certain critical level, called the growth threshold (HELLIWELL *et al.*, 1980). It is observed that as the level of the input signal is slowly increased the growth rate sud-

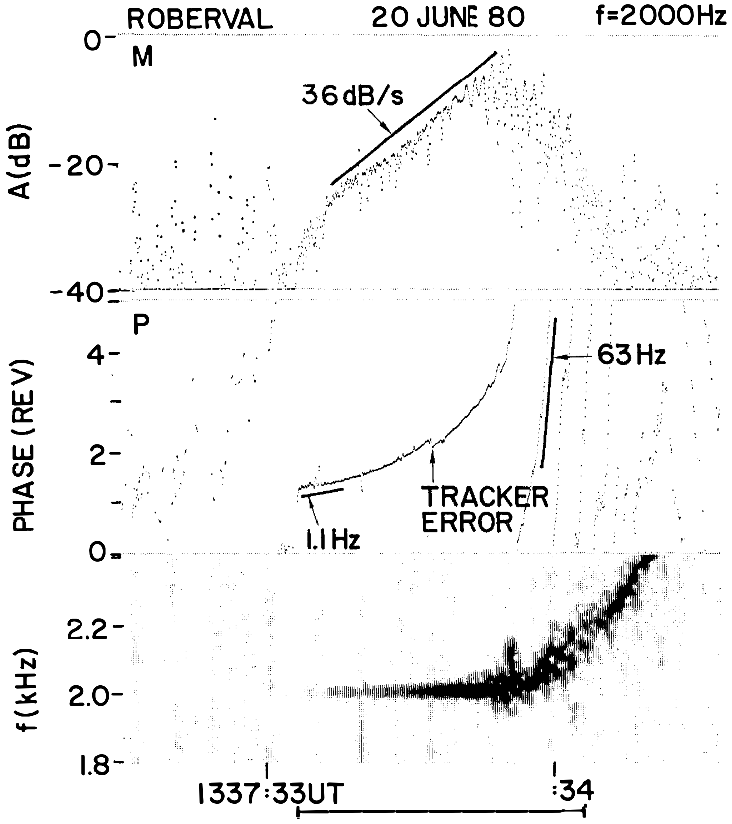

Fig. 2. Digital analysis of dynamic spectrum (bottom panel), phase track (middle panel) and amplitude in dB of a one-hop pulse injected from Siple Station at 2 kHz. Transmitted 1-s pulse corrected for path delay is shown at bottom. One REV=360°.

denly increases as shown in Fig. 3. Just below this level there may be some amplification but no unstable growth. The growth threshold level changes with time, sometimes as much as 20 dB in a few minutes. It provides a possible explanation for the occurrence of whistlers that are preferentially associated with large lightning discharges, since whistlers themselves are expected to exhibit the same growth threshold as seen on the Siple signals. If the lightning flash is too weak then the injected quasi-coherent whistler wave does not exceed the threshold for exponential growth and hence the received whistlers are weak. When the input whistler-mode signal exceeds the growth threshold it is frequently observed that the signal grows 20 or 30 dB before it saturates. Thus we see that the stronger input signals are significantly enhanced by growth and hence stand out in the observations. It should be noted in passing that although one-hop whistlers received on the ground may show many components and hence may appear relatively incoherent, the individual whistler components actually travel in separate ducts. Hence the one-hop whistlers can be expected to be relatively pure-toned signals within the interaction region (see Fig. 1). Higher order (*e.g.*, 2-hop, 3-hop, etc.) echoes can couple between ducts, causing reduced coherence in the interaction regions, and hence reduced growth.

One of the interesting subtleties of the triggering of emissions is what appears to be "post triggering" suppression of the carrier. A CW signal is ramped up in amplitude

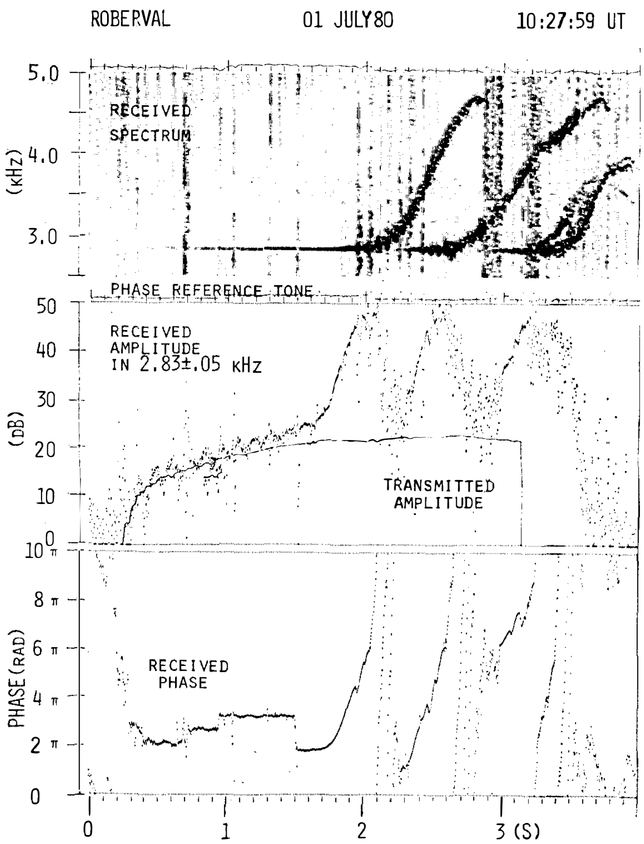

Fig. 3. Digital analysis of 3-s long pulse showing threshold effect for growth and triggering. (a) Dynamic spectrum. (b) Amplitude vs. time of received signal (shown by dots) within a 100-Hz band centered at transmitter frequency. Amplitude of transmitted signal is ramped up with time as shown by solid line. (c) Received phase showing onset of phase advance close to time of fast temporal growth. The earlier phase jumps were caused by sferics appearing in panel (a).

past the threshold at which temporal growth begins. Following triggering there is a reduction of the background signal, at the carrier frequency, to a level well below the unamplified level as evidenced by the pre-threshold recording (see Fig. 3). One possible explanation for this interesting result is an asymmetrical interference with the distribution function by the triggered "riser." The riser interacts with electrons on the lower velocity side of cyclotron resonance, disrupting the bunching of their phases by the weaker input carrier. The result is that the only stimulated components which can modify the carrier amplitude are at slightly higher velocities where the stimulated radiation may be able to subtract from the carrier. As soon as the triggered emission has moved up sufficiently in frequency it no longer influences the particles that are locally resonant with the carrier and hence the normal exponential growth of the carrier can be resumed as shown in the Fig. 3. Attenuation of an input signal by a triggered emission is an important feature of the general problem of multi-frequency mutual interaction.

3. Two-frequency Response

A set of simple experiments on the nonlinear wave particle interaction has been performed using two coherent waves of variable relative amplitude and variable relative frequency. These experiments have revealed several interesting effects. First, it has been observed, as shown in Fig. 4, that when two equal intensity signals are spaced about 20 Hz there is little or no growth of the carriers. However there still may be strong sidebands that are separated from the carriers by integer multiples of *Df*. When one of the two carriers is turned off leaving the other carrier as a single signal the latter immediately begins to grow at the normal single frequency exponential rate. Such prompt recovery from suppression contrasts with the so-called "quiet-band" effect in which both the onset and the recovery require many seconds (RAGHURAM *et al.*, 1977; CORNILLEAU-WEHRIN and GENDRIN, 1979).

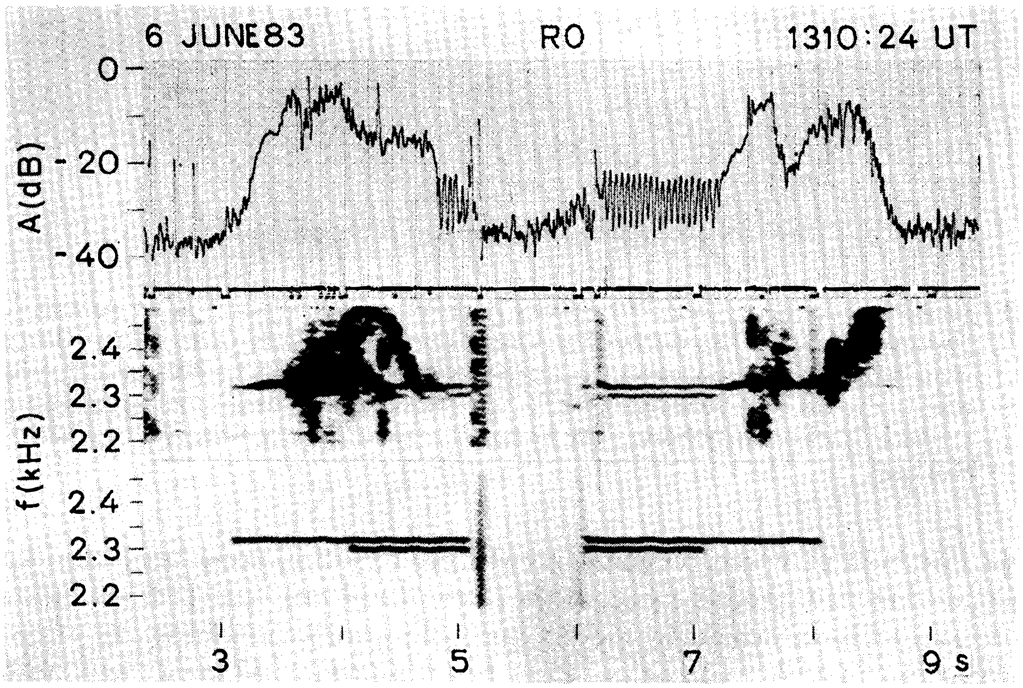

Fig. 4. Single and double (Df = 20 Hz) frequency response. Bottom panel shows transmitted format; middle panel, signals received at Roberval; top panel, total intensity of received signals in 300 Hz band.

Although it is tempting to assume that electrons trapped in the wave's potential well are the source of sidebands, satellite measurements suggest that the Siple signal at the input to the interaction region is usually well below the trapping level. It is estimated that the Siple input signal is typically of the order of .1 to .2 pT as it approaches the equator (INAN *et al.*, 1977; RASTANI *et al.*, 1985). This input intensity is below the trapping level for most models and thus argues against the use of theories that are based on the trapping of electrons by the wave. Furthermore single-frequency growth is known to occur at relatively low input signals, depending on the growth threshold, requiring that the process for amplification be effective at signal intensities

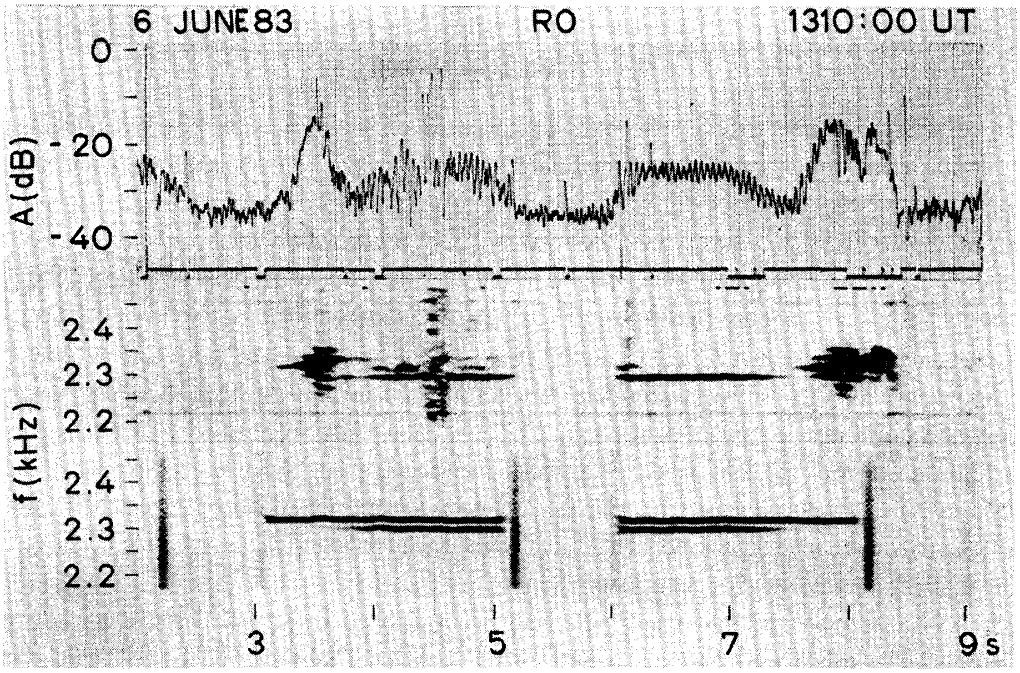

Fig. 5. Same as Fig. 4, except lower frequency component ramped in amplitude at rates of +20 dB/s in 3 to 4 s period and at −20 dB/s in 7 to 8 s period. Transmitted format is aligned in time with principal received component.

well below the trapping level (CARLSON *et al.*, 1985). A qualitative 'beat triggering' model for the generation of sidebands has been proposed (HELLIWELL *et al.*, 1986). Each beat between two adjacent frequencies constitutes a signal that starts the amplification process at the average frequency of the two carriers. As the beat envelope approaches zero intensity an emission is triggered which may then be cut off by the following beat which has the opposite radio frequency phase. The result is a series of weak emissions triggered between successive beats. Each such emission is modulated in both frequency and amplitude which can account for the observed asymmetry in the sideband spectrum. When one of the input signals is attenuated with respect to the other, two changes occur. First, the stronger of the two carriers is permitted to grow significantly and second, the beat between the two signals modulates the amplified signal creating even stronger sidebands. Such sideband enhancement illustrated in Fig. 5.

As the frequency spacing between the beating carriers changes we note interesting changes in the sideband character. The maximum number of sidebands occurs when *Df* is near 10–15 Hz whereas the maximum frequency range (∼100 Hz) of the sidebands tends to be independent of *Df*. In other words as *Df* increases, the number of sidebands is reduced but the overall spacing tends to remain the same. This result shows that the interaction mechanism has a high frequency cutoff, resulting possibly from the electron's inertia. One important feature of beat triggered sidebands is that they constitute a source of new frequencies. Sidebands can equal or even exceed the carriers in strength. Thus any pair of signals injected into the medium is capable of interacting with one another to produce sidebands extending as much as 100 Hz above and below the frequencies of the input signals.

4. Noise Stimulation

An obvious extension of the two-frequency experiments is the transmission of many frequencies in a form that simulates natural hiss. The simulation of hiss in a rigorous way would be difficult with any transmitter that is peak power limited, such as that at Siple Station, since random noise has wide variations in peak amplitude. However a method has been devised to partially get around this problem, based on the dispersive effect of the magnetosphere on the transmitted signals. By frequency modulating a constant amplitude carrier it is possible to create a signal whose power spectrum is noise-like. The individual wavelets, as shown in Fig. 6, then propagate at different phase and group velocities. By the time that they arrive at the equatorial plane dispersion has caused these wavelets to overlap in time by amounts that vary with *Df* and the parameters of the model. The resulting irregular phase shifts between wavelets cause the amplitude to vary in a way that more closely resembles true white noise, a sample spectrum for which is shown in Fig. 6d.

Often the received elements of the noise appear to combine with one another to form extended emission elements resembling natural chorus. Examples are shown in the Fig. 6b. These forms may grow several dB above the background level. The limited amplitude growth of the noise elements can be explained by the presence of adjacent noise pulses which partially suppress growth. Thus the noise simulation experiments have revealed a process whereby fragmented wavetrains are connected

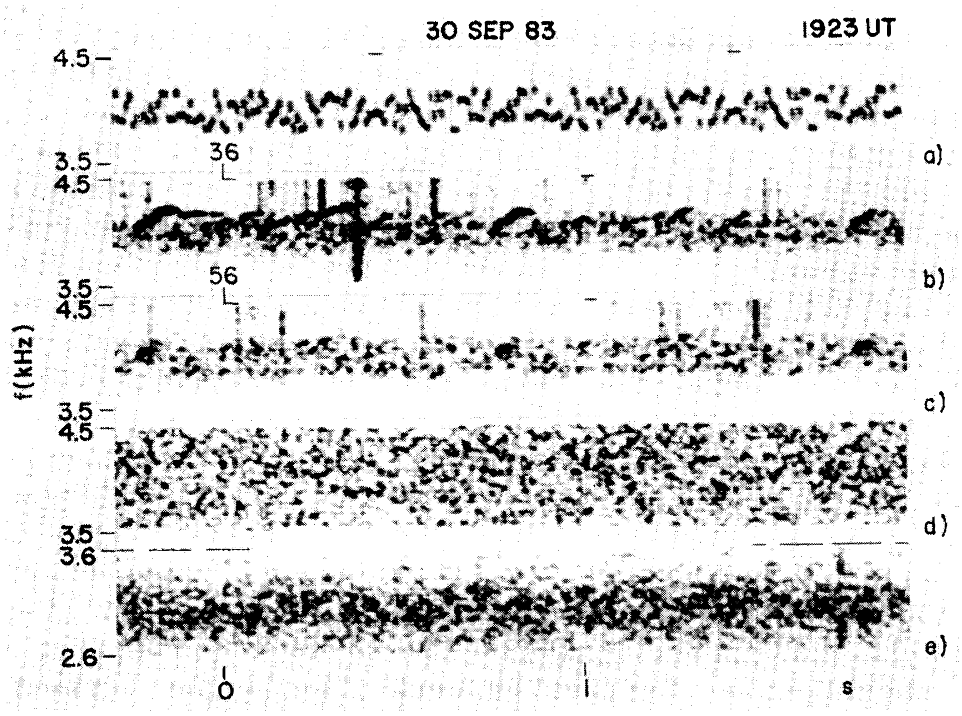

Fig. 6. Hiss spectra for 20-Hz filter bandwidth. (a) Transmitted spectrum, with 1-s periodicity. (b), (c) Received spectra taken 20 s apart showing changes and similarities in 1-s pattern. (d) Spectrum of hiss from a laboratory random noise generator. (e) Spectrum of natural hiss received at Roberval on February 14, 1977 at 1216 UT.

together to form more coherent structures that resemble the chorus phenomenon. How this might occur can be understood if we invoke the second-order resonance effect in which coherent frequency ramps are amplified in the same way as the constant frequency signals (HELLIWELL and KATSUFRAKIS, 1978). Thus as two or three separated wave trains propagate along the field-aligned path they encounter regions in space where the interacting electrons can coherently interact in sequence with two or more wavelets, thereby creating in effect a spliced wavetrain. The result is more phase bunching and a stronger emission.

5. Magnetospheric Line Radiation

The first report of line radiation from the magnetosphere linked the results to radiation from the Canadian power system (HELLIWELL *et al.*, 1975). However it was noted in that paper that the magnetospheric line radiation was not located exactly at harmonics of the power line frequencies. Deviations as much as 20–30 Hz were observed. Since that time other measurements made in satellites and on the ground have revealed the presence of multiple line radiation in which the frequencies of the lines vary slowly and independently of the fixed power system frequencies (MATTHEWS and YEARBY, 1981; BELL *et al.*, 1982). A new example of line radiation obtained at

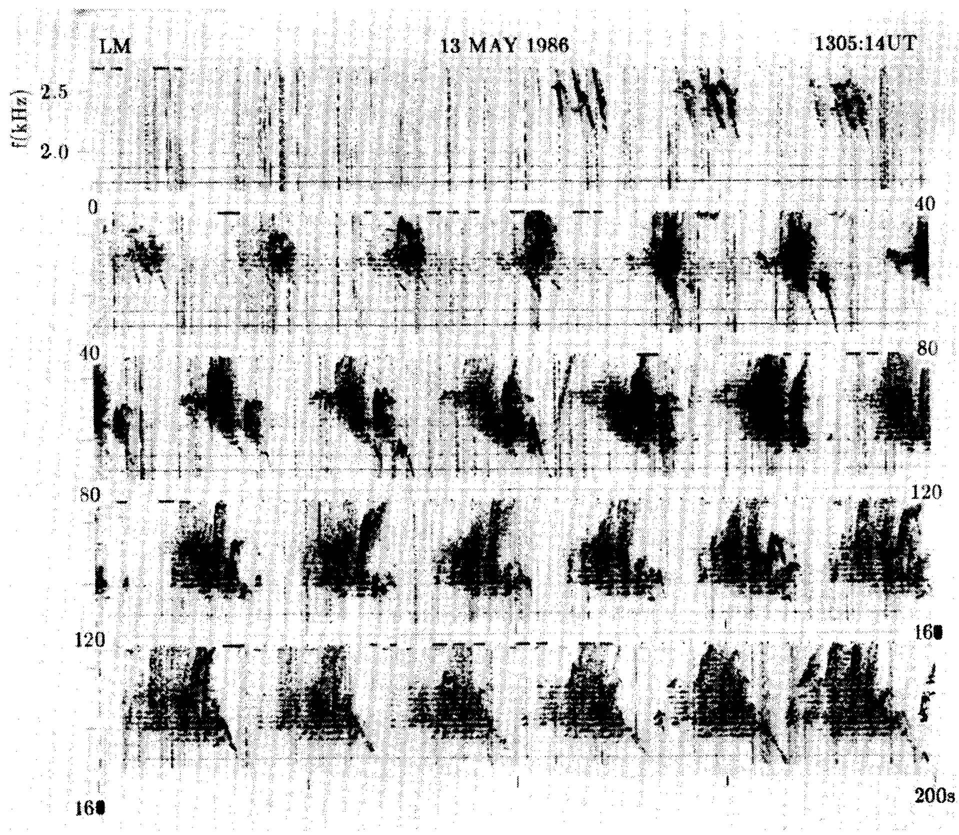

Fig. 7. Periodic emissions that begin on the lower frequency components of falling-ramp test signals from Siple Station. Two-hop echoing period is ~6.1 s at f=2.2 kHz. Quasi-horizontal line structure is well-defined beginning with the 7th hop. Both dispersive and nondispersive discrete elements can be found.

Lake Mistissini, the conjugate point to Siple Station, is shown in Fig. 7. In this event a sequence of three falling frequency ramps was transmitted from Siple Station and was first received at 1305:36–39 UT following a one-hop trip from Siple Station to Lake Mistissini; it then began to echo (3rd hop at 1305:42–45 UT) and to change shape as a result of emission triggering. As the echoes evolved in time a line structure began to emerge, becoming well established some 40 s after the start of the event. The echoing of these lines is clearly seen in Fig. 7. Multiple echoes of hiss and discrete emissions and their slow changes with time are well known from previous studies of natural emissions (HELLIWELL, 1965). The new feature of the event shown in Fig. 7 is the nearly horizontal line structure which repeats from one echoing burst to the next. The spacings of these lines averages approximately 45 Hz and thus has no apparent connection with either 50 or 60 Hz power systems. Furthermore these lines show slow upward and downward frequency drifts of the order of 50–100 Hz/min, similar to results reported elsewhere (BELL *et al.*, 1982). The narrow light lines at the bottom of the record in Fig. 7 are identified as induction lines from the Canadian power system and serve as a convenient frequency reference. Although the line drift appears to be independent of the induction lines, there is a suggestion of cutoffs and enhancements of emissions where the slowly drifting magnetospheric lines cross the induction lines. Thus we are faced with the problem of explaining the maintenance of a line system that appears to first order to be little affected by radiation from the power system.

A clue to a possible explanation of magnetospheric line radiation is offered based on the two-frequency beat triggering experiments described above. Here we see that the components of the transmitted signal suppress one another for frequency spacings that are less than about 70 Hz. The maximum suppression occurs at roughly $Df=20$ Hz. The line radiation shown in Fig. 7 shows spacings of about 45 Hz which lies between the limits for the controlled experiment results. Thus we are led to postulate that the maximum line spacing is set by a balance between suppression and growth. If two lines start to approach one another they are mutually suppressed, causing those frequency components with larger spacings to grow more rapidly. Production of new lines might be fostered by interaction between existing lines and weak background radiation from the power grid. However the power grid radiation is difficult to detect in its unamplified state, so this idea remains to be verified.

One might postulate that the lines originate in input signals from Siple or in whistlers and that irregular enhancements in the intensities of these signals at different frequencies tend to stimulate preferred growth at spaced frequencies as a result of the threshold effect. These in turn could then create their own sidebands which drift up and down in the frequency spectrum until they reach the limits of possible amplification through the echoing process. Factors that may play a role in this phenomenon include the growth threshold, adjacent channel suppression, growth rate, and echoing efficiency at the ends of the path.

6. Hiss-chorus Connection

The main features of a possible equilibrium model have been presented in connection with two-frequency experiments and noise simulation experiments. The magnetospheric line radiation example just discussed illustrates a possible application of these results. In general terms we can argue from the basic experiments that there are two fundamental processes in the magnetosphere involving wave-particle interactions. One is the Coherent Wave Instability in which coherent waves are preferentially amplified and triggered compared with noise. The other is the break-up of coherent waves into less coherent components through processes such as beat triggering. This reduction in coherency could lead to a noise-like spectrum. The wave-train splicing process observed in the noise experiments tends to make the noise more coherent. The various factors influencing these processes vary with time in such a way that at any given time there could be a wide variation in the properties of the equilibrium situation. The essential point is that there can be simultaneous conversion of relatively coherent signals into noise and the conversion of noise elements into more coherent structures, such as chorus. Such an equilibrium might account for the simultaneous presence of chorus and hiss often reported by satellites and by ground stations.

7. Conclusions

An important result from recent controlled experiments at Siple Station is the demonstration that natural noise can be simulated using existing equipment. The initial results from these experiments suggest that most of the phenomena that are commonly seen on the ground from the magnetosphere can eventually be simulated with controlled experiments. It should be possible therefore to experimentally determine in quantitative terms the input-output relationships for virtually any form of input signal. Once all of the phenomena have been duplicated and the conditions for their creation are known it should be easier to create realistic models of the mechanism of interaction. These results can serve as an important driver in the construction of computer simulation models for wave-particle interactions in plasmas. New questions that must be explored include the area of sub-harmonic generation which has not yet been mentioned in this paper. However there is preliminary evidence indicating the formation of integer sub-harmonics as a part of the process of sideband generation. Thus it appears that the spectral fine structure of VLF emissions from the magnetosphere may be surprisingly rich and hence may find new uses as a tool for diagnostic study of the magnetosphere.

Conjugate point measurements of the type described here provide reproducible measurements of highly nonlinear wave-particle interactions and should be developed fully for the benefit of solar terrestrial physics. What is needed are more experiments at different latitudes where different parts of the magnetosphere plasma can be reached. One possibility is to establish facilities on the Antarctic continent at somewhat higher latitudes so as to obtain easier access to the outer regions of the magnetosphere. Lower frequencies and more power will be required to carry out these experiments. Consideration should be given to the development of an internationally supported facility for which the costs could be shared, and the benefits made available to all interested research groups.

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