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VLF Wave Injection Into the Magnetosphere From Siple Station, Antarctica

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Radio signals in the 1.5- to 16-kHz range transmitted from Siple Station, Antarctica ($L = 4$), are used to control wave-particle interactions in the magnetosphere. Observations at the conjugate point show signal growth and triggered emissions including risers, fallers, and hooks. Growth rates of the order of 100 dB/s and total gains up to 30 dB are observed. Triggered emissions may be cut off or have their frequency rate of change altered by Siple pulses. Similar effects occur in association with harmonics from the Canadian power system. The observed temporal growth is predicted by a recently proposed feedback model of cyclotron interaction. Plasma instability theories predicting only spatial growth are not in accord with these observations. Possible applications include study of nonlinear plasma instability phenomena, diagnostic measurements of energetic particles trapped in the magnetosphere, modification of the ionosphere through control of precipitation, and VLF communication through the magnetosphere.

This is a report of the first results of a new experiment to control wave-particle interactions in the magnetosphere, using VLF waves. Coherent whistler mode signals were injected into the magnetosphere in the 1.5- to 16.0-kHz range from a 100-kW transmitter located at Siple Station, Antarctica. The output signals were observed at the Siple conjugate point near Roberval, Quebec. The signals followed field-aligned ducts near $L = 4$ (see sketch in Figure 1*a*). Among the new results is the observation that the signal received at Roberval generally shows exponential growth as a function of time, with growth rates of the order of 100 dB/s. Total power gains of up to 3 orders of magnitude (30 dB) have been observed. Following the exponential growth phase, emissions at new frequencies are usually triggered, in the form of narrow band rising or falling tones. A by-product of these investigations is the finding that VLF radiation at harmonics of the commercial power system appears to be present in the magnetosphere, modifying the spectrum of the triggered emissions.

In the following section of this paper we review briefly the previous experimental work on VLF wave injection into the magnetosphere. In the next three sections we describe the siting of Siple Station, the apparatus, and some of the first experimental results. In the last section we discuss these results and some possible applications.

PREVIOUS WORK

Man-made whistler mode signals were first detected at Cape Horn from Station NSS on 15.5 kHz, located at Annapolis, Maryland [*Helliwell and Gehrels,* 1958]. Later discrete VLF emissions were observed to be triggered by Morse code transmissions from Stations NPG on 18.6 kHz and NAA on 14.7 kHz [*Helliwell et al.,* 1964]. Nearly all triggering was caused by the Morse dashes. When the dots did trigger, the resulting emissions were always weak falling tones [*Lasch,* 1969]. Emission triggering by the long (~1 s) pulses from a relatively low power (~100 W) Omega transmitter operating on 10.2 kHz was also observed [*Kimura,* 1968]. Observations during a drifting duct event showed that triggering was enhanced when the transmitter frequency was near one half the equatorial gyrofrequency [*Carpenter,* 1968]. These results could not be interpreted in terms of existing theories of plasma instability. To obtain further experimental data, a transmitter was needed that could operate at lower frequencies and whose power, pulse length, and frequency could easily be varied.

The next step was construction of a 33.6-km-long horizontal dipole at Byrd Station ($L = 7.25$) in 1965 [*Guy,* 1966]. This antenna was shared by a VLF step frequency sounder operated by the University of Washington and a VLF magnetosphere sounder operated by Stanford University. The dipole was laid on the ice to lower its Q and hence increase its bandwidth. Soundings of the D and E regions were successfully carried out over the frequency range 3–30 kHz [*Helms et al.,* 1968]. Whistler mode transmissions in the range 6–9 kHz were observed by the Stanford University VLF receiver on the Ogo 4 satellite as it flew over the transmitter in the upper part of the F region. However, the signals were too weak to excite detectable whistler mode signals in the conjugate hemisphere. One reason was the low efficiency of the low Q antenna and another was its high latitude. This high latitude meant that signals from the transmitter would first have to travel about 1000 km in the lossy earth ionosphere wave guide to reach the field lines on which propagation to the conjugate hemisphere was commonly observed.

SIPLE STATION

From the Byrd experiments it was clear that the transmitter would have to be moved to a lower geomagnetic latitude. The desired site characteristics were (1) proximity to the plasmapause ($L \approx 4$), (2) a stable ice sheet at least 2000 m thick, and (3) a conjugate point readily accessible to year-round manned operation. A site satisfying these criteria was found at 76°S and 84°W ($L = 4.1$) and was occupied in the austral summer of 1969. It was named Siple Station; its conjugate point is near Roberval, Quebec (48°N, 73°W).

With the aid of impedance measurements made on a test dipole erected above the snow during the 1969–1970 austral summer a 21.2-km-long operational antenna was designed [*Raghuram et al.,* 1974]. It was constructed during the austral summers of 1970–1971 and 1971–1972. The measured resonant frequency is 5.1 kHz, close to half the minimum gyrofrequency (~6 kHz) on the field line through Siple Station. The bandwidth is about 2 kHz. The radiation efficiency at 6 kHz is estimated to be 4%. The average elevation of the

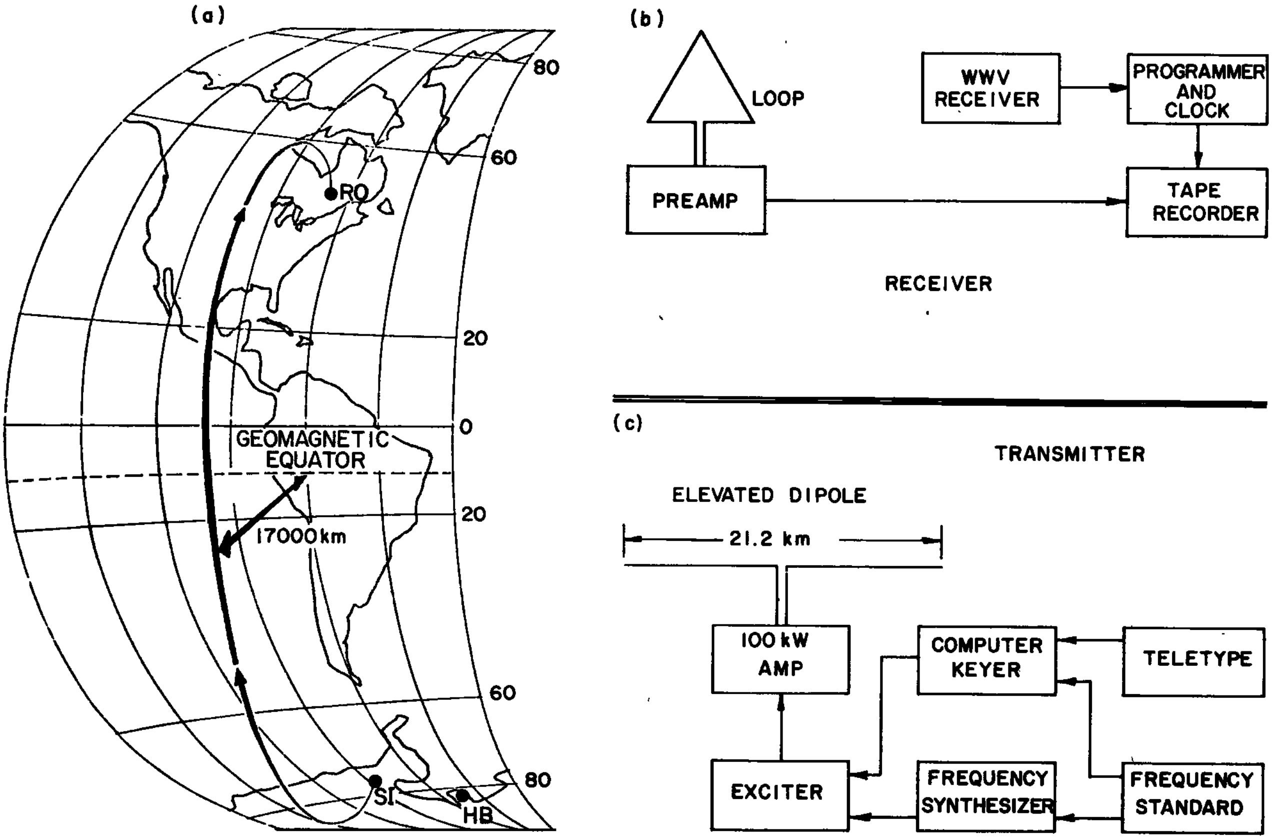

Fig. 1. (*a*) Sketch of magnetospheric path from Siple Station (SI), Antarctica, to Roberval, Quebec (RO); HB is Halley Bay. (*b*) Roberval VLF receiver block diagram. (*c*) Siple VLF transmitter block diagram.

antenna above the snow surface was initially 6 m, with provision for periodically raising the antenna to compensate for an annual snow accumulation of 1–2 m.

A year-round manned facility, including the 100-kW high-efficiency solid state VLF transmitter from Byrd Station, was constructed during the austral summer of 1972–1973. Various passive experiments were also installed, including whistler and VLF emission recordings (Stanford University), magnetic field intensity (Bell Laboratories), magnetic pulsations (University of Minnesota and University of New Hampshire), and ionospheric absorption (University of San Diego).

Operation of the passive experiments began in early 1973.

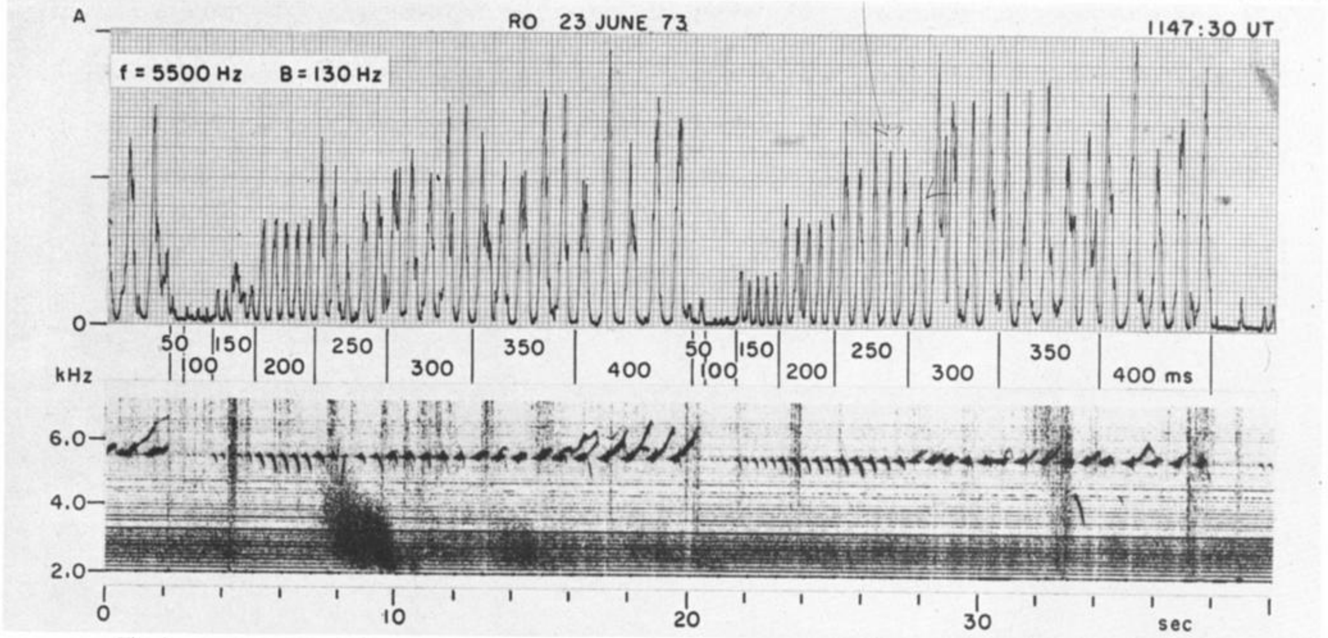

Fig. 2. Variable pulse length sequence received at Roberval. Lower panel shows the spectrum, and upper panel shows the amplitude in a 130-Hz bandwidth centered on 5.5 kHz. Pulse lengths vary from 50 to 400 ms in 50-ms steps as is indicated by the numbers between panels. A two-hop whistler, with echoes at ~3 kHz, appears at 8–10 s and originates in the sferic at 4.2 s. A strong well-defined two-hop whistler component extending up to 5.5 kHz is seen at about 8.2 s and corresponds to the one-hop delay of the Siple pulses.

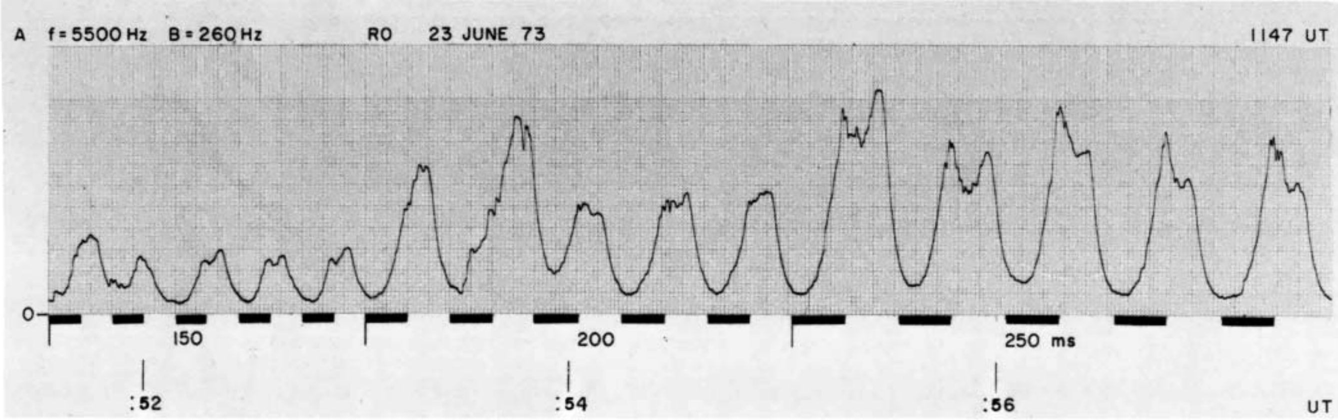

Fig. 3. Pulse envelope of the 150-, 200-, and 250-ms pulses in the second 18-s sequence shown in Figure 2. Solid bars represent the transmitted pulses corrected in time for the one-hop travel time of 2.02 s.

The VLF transmitter was placed in service in April 1973 and has since operated an average of 6 hours a day on different frequencies, with various modulation patterns and power levels. Most transmissions have been confined to the period 0800–1400 UT, with occasional transmissions during 0000–0800 and 1600–2000 UT. The fixed frequencies used so far are 1.5, 2.5, 3.5, 4.0, 4.5, 5.0, 5.04, 5.5, 5.52, 7.1, 7.6, 14, and 16 kHz, together with various frequency sweeps. The output can be frequency modulated (FM) or keyed on and off. A wide range of FM wave forms can be programed, including square waves and sawtooth ramps. Power output can be varied continuously from zero to maximum with the aid of a motor-driven variable autotransformer. Values between 0.4 and 100 kW have been employed up to date. In September 1973 the keying of the transmitter was placed under control of a minicomputer, so that unmanned operation over the full 24 hours could be achieved. A simplified block diagram of the transmitter is shown in Figure 1*c*.

The main observation point for the whistler mode signals from the Siple transmitter is Roberval, Quebec. A block diagram of the receiver is shown in Figure 1*b*. Continuous broad band tape recordings are made during all VLF transmissions from Siple Station. Synoptic recordings are made for 2 min every hour throughout the year, for studies of the plasmapause, whistler propagation, and VLF emissions. The tapes are sent weekly to Stanford University for spectrum analysis. Quick-look results are used to guide the future programing of the transmitter. Accurate timing of transmitted and received pulses is established by frequency standards at Siple and Roberval. These standards are calibrated regularly against Station WWV and are kept within a few milliseconds of UT.

Siple whistler mode signals have been observed by the VLF receivers on various satellites, including Imp 6 and Explorer 45 (D. Gurnett and R. Anderson, personal communication, 1973) and Isis 2 (F. Palmer, personal communication, 1973). Subionosphere signals from Siple have been observed at Halley Bay, Antarctica (K. Bullough, personal communication, 1973), and at Dunedin, New Zealand (R. Dowden, personal communication, 1973).

PRELIMINARY RESULTS

The occurrence of detectable Siple signals at Roberval is highly variable. They are seldom present when there is natural emission activity on the same frequency. Their appearance seems to depend on the prior existence of substorm activity. Although diurnal trends have yet to be established, we have found that the period around local sunrise is often active. A wide variety of spectral forms has been observed in the signals stimulated by the Siple transmissions, including risers, fallers, hooks, and interactions with other signals. Whistlers may on occasion show much stronger traces at frequencies above the transmitter frequency than at those below. Some of these phenomena are discussed in the following paragraphs. More details will be given on these topics in later papers.

When the Siple transmitter is first turned on for a daily run, the response of the magnetosphere is immediate. There appears to be no buildup time required to 'prime' the plasma. The first transmitted pulse exhibits the same amplification and triggering as later pulses.

One of the first experiments performed with the Siple transmitter was a study of the dot-dash anomaly mentioned above. A series of pulses of varying duration was transmitted at constant power. The pulses were formed by switching the frequency between 5.0 and 5.5 kHz. The pulse length was varied from 50 to 400 ms in 50-ms steps. Five pulses were transmitted at each length, giving this variable pulse length (VPL) sequence a total duration of 18 s.

Two typical examples of the 18-s VPL program as recorded at Roberval are shown in Figure 2. The spectrum (lower panel) shows significant activity only on 5.5 kHz, although there is a strong isolated falling tone at about 33 s triggered at 5.0 kHz. (Some of the other sequences (not illustrated)

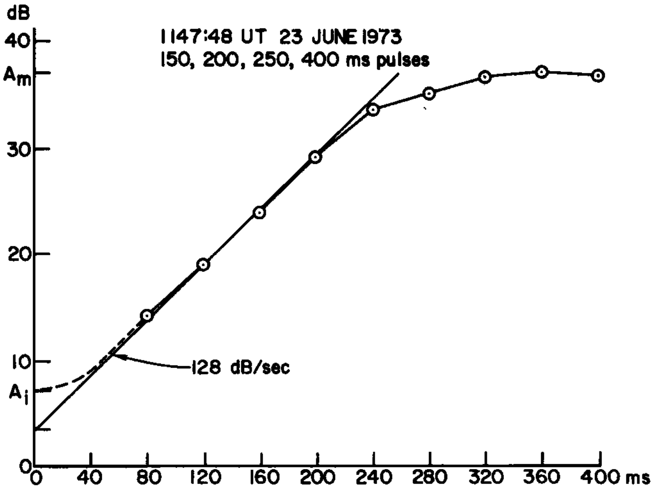

Fig. 4. Average amplitudes of output pulses as a function of time after the start of the received pulse. Straight line fit gives exponential growth rate of 128 dB/s. Total growth is $A_m - A_i = 30$ dB.

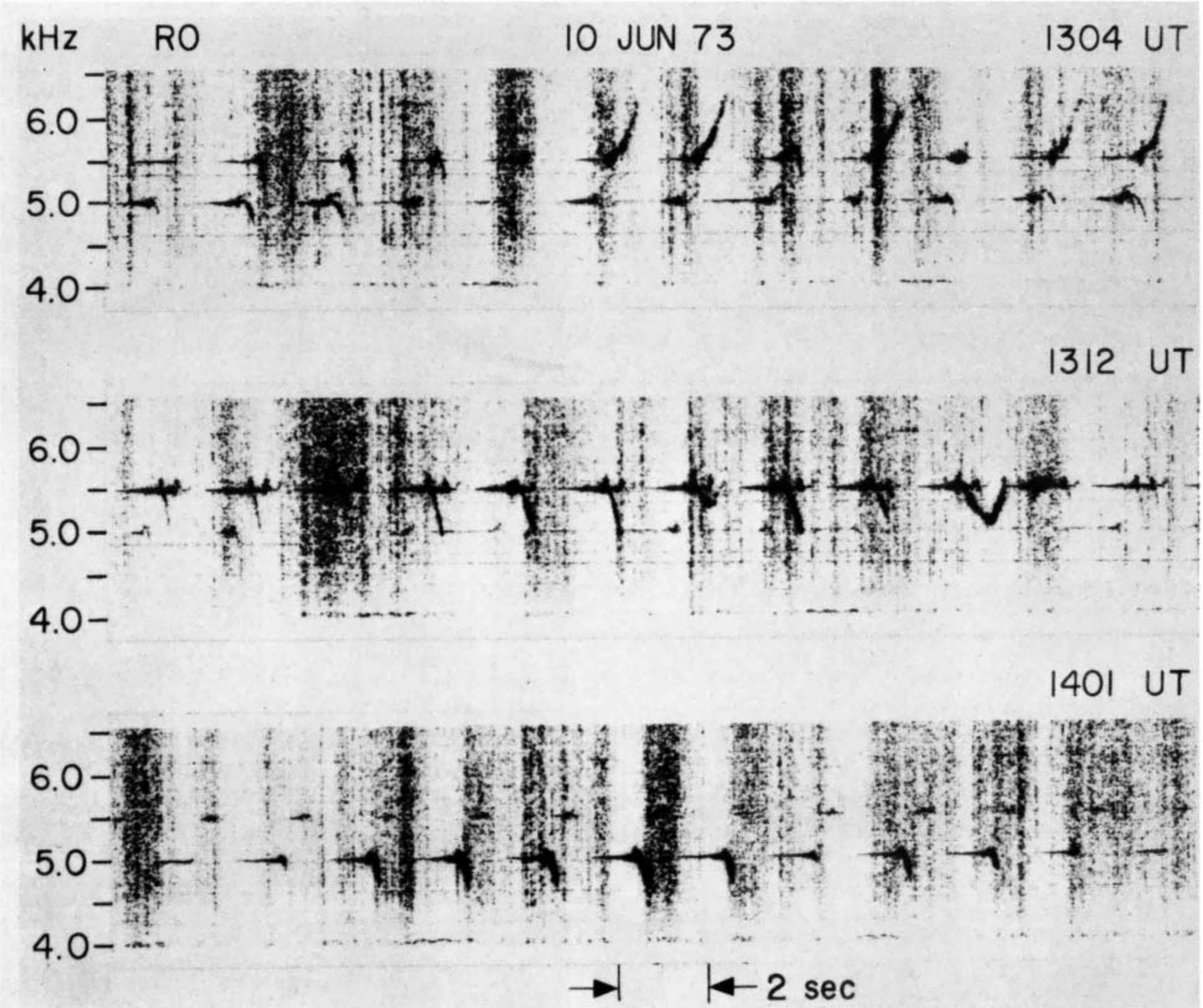

Fig. 5. Alternating 1-s transmissions on 5.0 and 5.5 kHz. Middle panel shows falling tones triggered at 5.5 kHz that are cut off by the weaker signals on 5.0 kHz. Triggering on two paths, separated about 0.4 s in time, is frequently present in the middle panel.

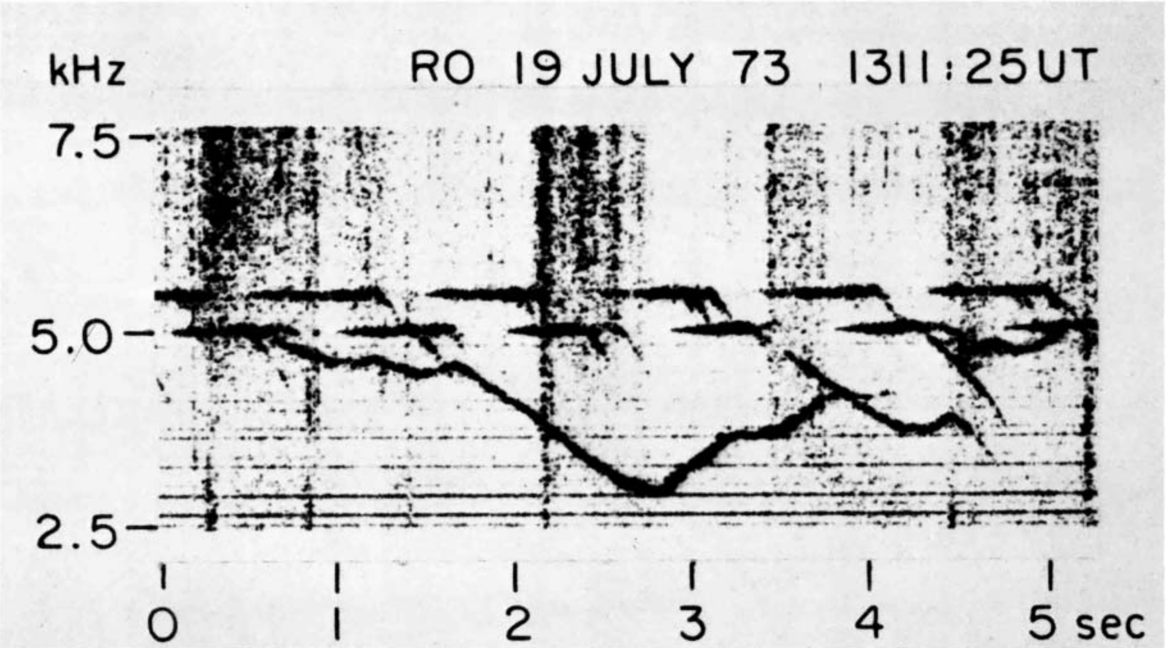

Fig. 6. Hooks triggered at 5.0 kHz show inflections and reversals in slope at power line harmonics, defined by the horizontal lines.

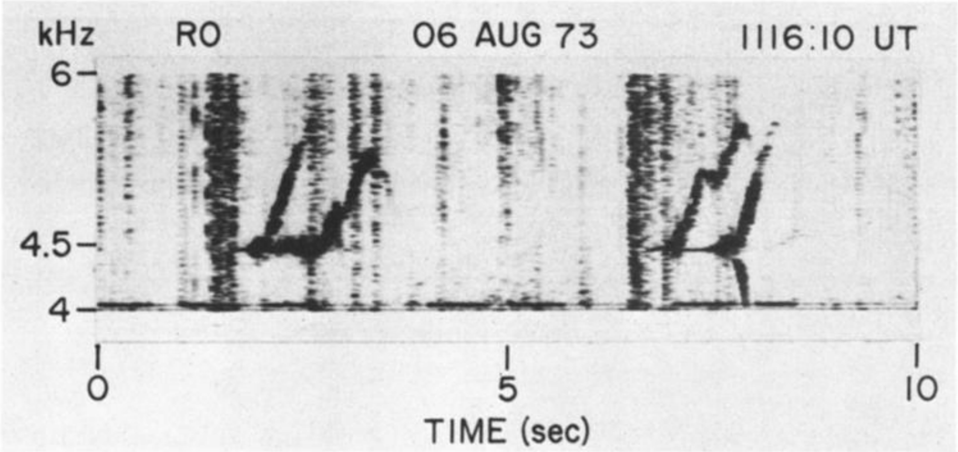

Fig. 7. Two 1-s pulses are transmitted 5 s apart at 4.5 kHz. Similar emissions are excited on two paths separated in group delay by about 0.7 s.

showed more activity on 5.0 kHz.) The relative amplitude in a 130-Hz band centered on 5.5 kHz is shown in the upper panel. It is clear that the intensity of both the whistler mode signal and its associated emission increases with pulse length. Except for the 50-ms pulses, which are too weak to be seen, each set of five pulses is clearly defined. For lengths less than 300 ms the peak intensity approximately doubles each time the pulse length is increased by 50 ms. This increase corresponds to a growth rate of 120 dB/s. For lengths of 350 and 400 ms the peak intensity is roughly constant, and thus it is indicated that saturation has been reached.

The pattern of triggered emissions is directly related to the pulse length, as can be seen from Figure 2. Triggered emissions first appear at the ends of the 150-ms pulses. All emissions first rise in frequency; they may then fall or rise depending on the length of the triggering pulse. For pulse lengths of 250 ms and less the terminal part of the emissions is a falling tone, whereas for pulse lengths of 300 and 400 ms they are mainly risers. The upper panel shows amplitude fluctuations, some of which appear to relate to preceding whistlers and ASE's (artificially stimulated emissions). Thus the third 250-ms pulse in the first 18-s sequence is reduced at the time of arrival of the two-hop whistler. Other reduced amplitudes can be associated with unusually strong preceding risers.

The systematic increase in pulse peak amplitude with pulse length shown in the upper part of Figure 2 implies a corresponding temporal growth of each pulse. An expanded version of a portion of the second VPL sequence of Figure 2 is given in Figure 3 to show the growth of each pulse. The solid bars below the trace represent the pulse input to the growth region. The leading edge of the input pulse does not coincide exactly with the minimum in the received signal because there is still some signal left from the emission triggered by the preceding pulse. If one begins at the minimum amplitude, it is seen that the output pulse grows exponentially with time until the input pulse terminates. The amplitude may then increase a little before it begins to fluctuate and decay.

The amplitudes of each output pulse were scaled over the period of the input pulse by using the 150-, 200-, 250-, and 400-ms pulses. (The 300- and 350-ms pulses were omitted because their amplitudes were contaminated by previously triggered emissions falling within the 130-Hz passband.) The averages of these amplitudes are plotted on a logarithmic scale in Figure 4 as a function of time with respect to their leading edges. The leading edge of the received pulse could be seen on the records only occasionally when the sferic levels were low. However, its time of occurrence was reliably estimated from the path delay and the known pulse transmission schedule. The estimated initial intensity of the received pulse is plotted as A_i on Figure 4. Between about 80 and 200 ms the growth is seen to be purely exponential, the rate being

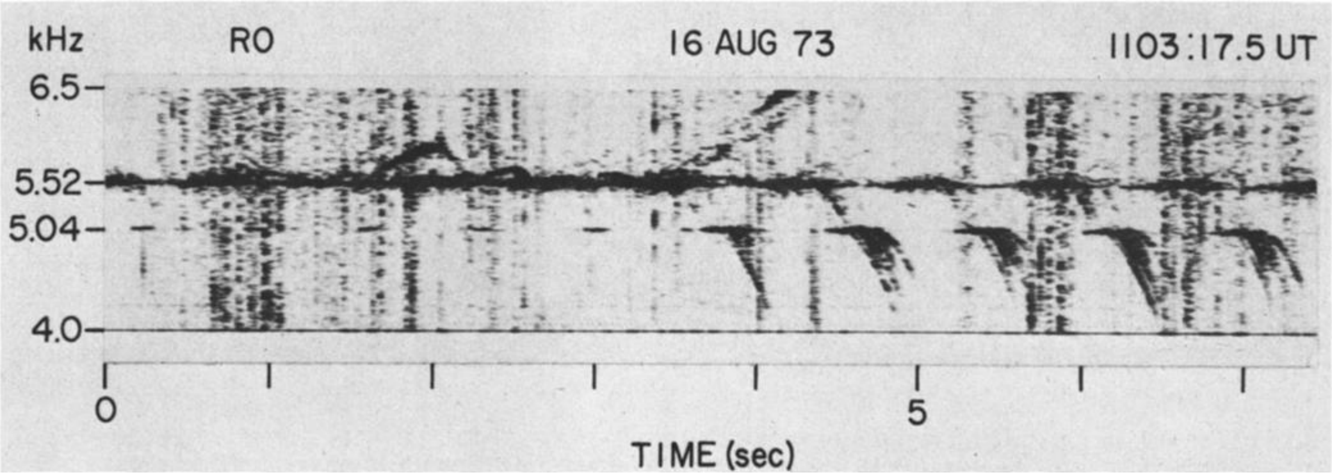

Fig. 8. At 5.04 kHz the first five pulses are 100 ms in length separated by 600 ms (the pulse length on 5.52 kHz). They do not trigger. The last five pulses are 200 ms long, also separated by 600 ms, and they trigger falling tones on at least four separate paths.

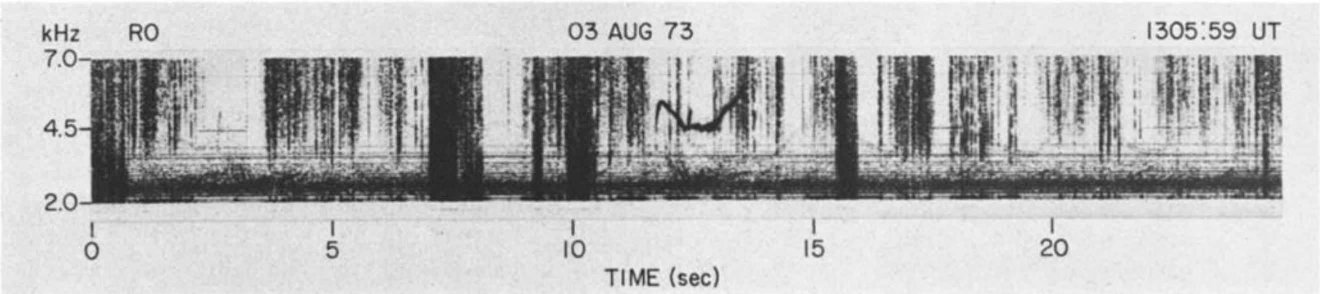

Fig. 9. Pulses of 1 s were transmitted every 5 s on 4.5 kHz. In the center of the record a whistler-triggered falling tone is entrained by the Siple pulse.

128 dB/s (14.7 Np/s). Beyond 200 ms the growth levels off, the saturation level A_m at 30 dB above the estimated input intensity being reached.

Alternate transmission on two frequencies has led to an interesting observation, illustrated in Figure 5. The ASE's triggered at 5500 Hz are frequently cut off by the signal 5000 Hz. The hook near the right side of the middle panel is cut off when its frequency returns to the starting frequency, where it encounters the beginning of the next pulse.

Emission cutoff or slope change may occur at frequencies not connected with known transmitters. This effect had been observed in spectra of triggered emissions [e.g., *Helliwell*, 1965, Figure 7–62*b*], but it had not been explained. An example from the present experiment is shown in Figure 6, in which two triggered hooks are observed to inflect or reverse slope at various frequencies. These frequencies are associated with the horizontal lines on the record, which are harmonics from the Canadian power distribution system. We offer as a possible explanation that harmonic radiation from the Canadian power grid is amplified in the magnetosphere and affects emissions in exactly the same manner as the Siple pulses. When the frequency of an emission approaches an amplified power line harmonic, the emission is cut off or the slope is modified. Support for this interpretation was found in a coincident increase in the intensities of certain power line harmonics observed at Eights Station and its conjugate, Quebec City, on October 17, 1963, at 2029 UT. This case will be discussed in a later paper.

Acceptance of the power system radiation hypothesis would help to explain a puzzling characteristic of periodic emissions. This is their tendency to trigger repeatedly at the same frequency [*Helliwell*, 1965]. In this situation the power line radiation might act to 'entrain' the echoing wave packets, causing each new emission to start at a particular power line harmonic. Since discrete VLF emissions are known to induce electron precipitation [*Rosenberg et al.*, 1971], it follows that if power line radiation exists in the magnetosphere, it may affect the terrestrial radiation belts. Further tests of this hypothesis are clearly needed before it can be accepted without doubt.

Among other features of interest are the following:

Multipath ASE's. Figures 7 and 8 show the triggering of similar emissions on separate paths. When this happens, it is possible for the spectral trace of an emission on one path to cross the trace of a signal or emission on another path. An example of this crossing effect appears in the middle panel of Figure 5, at 5.5 kHz. The first emission first rises, then falls, crossing 5.5 kHz after the triggering pulse with the shorter delay has terminated. However, the triggering pulse on the path with the longer delay is still present and therefore appears to cross the falling tone. Usually, however, the traces of emissions generated on the same path do not cross one another.

Entrainment. At about 12 s in Figure 9 a strong whistler-triggered falling tone appears to be 'captured' or entrained by the Siple pulse. The total signal remains strong but fluctuates about the transmitted frequency of 4.5 kHz. Then when the transmitted pulse terminates, a strong rising tone is initiated. The two pulses before and the two pulses after this event, however, are seen to be relatively weak.

Pulsations. Figure 10 shows a key down transmission of 10-s duration, in which ASE's are triggered at slightly less than 1-s intervals. After each ASE the carrier is suppressed, as in the case of Figure 2. The effect appears similar to the sup-

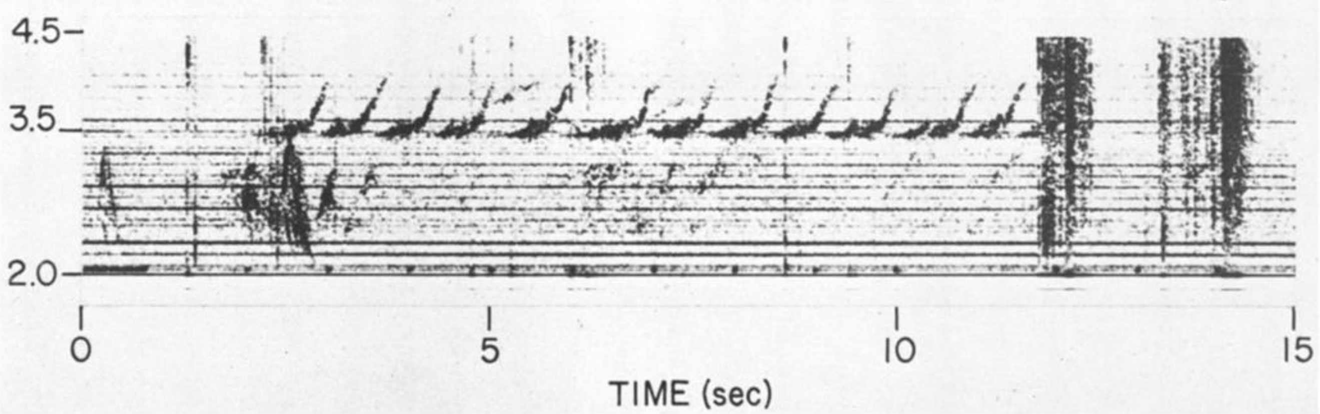

Fig. 10. A 10-s key down transmission on 3.5 kHz pulsates in the form of risers, occurring regularly with spacings averaging slightly less than 1 s. After each riser the signal first grows at the transmitted frequency before breaking into the next riser.

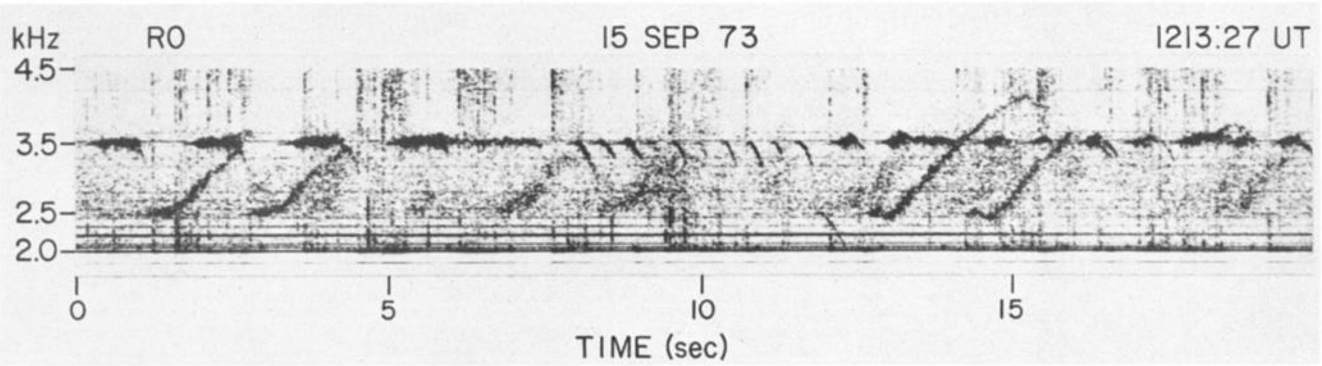

Fig. 11. Simultaneous triggering on 2.5- and 3.5-kHz FSK (frequency shift keying) program. At 3.5 kHz the first four pulses are 800 ms long, the next 10 are 100 ms long, the next 10 are 200 ms long, and the last 10 are 400 ms long. At 2.5 kHz, two adjacent 800-ms pulses trigger risers, beginning at 1 and 2.6 s, respectively. These two risers are each followed by three-hop and five-hop echoes. The first and fourth pulses of the 400-ms group at 2.5 kHz trigger hooks that also echo.

pression effect seen on three-phase periodic emissions [*Brice*, 1965]. It appears to differ from the pulsations observed on NAA key down transmissions [*Bell and Helliwell*, 1971] that were limited to the carrier frequency.

Frequency range. Frequencies from 1.5 to 16.0 kHz have been transmitted from Siple, whereas signals have been detected at Roberval only between 2.5 and 7.6 kHz. An example of triggering at 2.5 and 3.5 kHz is shown in Figure 11. The risers triggered at 2.5 kHz produce whistler mode echoes and are the lowest frequency emissions so far observed from the Siple transmitter.

DISCUSSION AND CONCLUSIONS

The observation of temporal growth, as shown in Figure 4, can be explained by a recently proposed model of cyclotron interaction with feedback included [*Helliwell and Crystal*, 1973]. Most published theories of cyclotron interaction in the magnetosphere omit the effect of feedback and derive a spatial growth rate. According to such theories [e.g., *Liemohn*, 1967] all parts of a finite wave train should exhibit equal growth. Our observations show instead that the input wave triggers an oscillation that grows exponentially with time until the input signal terminates or until the gain reaches ~30 dB.

An important question remaining to be answered is whether the maximum oscillation amplitude observed in these experiments is the maximum that can be obtained from the magnetosphere. Another question is the mechanism by which externally excited signals, such as the Siple pulses and the power line harmonic radiation, can affect emissions and whistlers. Not one of these results has been predicted, or even explained, by analytical plasma instability theories. Therefore further magnetospheric VLF wave injection experiments are needed for the benefit of both magnetospheric physics and laboratory plasma physics.

An expected by-product of emission stimulation by the Siple signals is modification of the energy and pitch angles of the interacting particles. Modification experiments with natural whistler mode waves [*Rosenberg et al.*, 1971; *Helliwell et al.*, 1973] have produced X rays and enhanced ionization in the *D* region. In future Siple transmitter experiments such precipitation effects will be sought. It may then be possible to control X-ray production, ionization, and light emissions in the ionosphere. New types of quantitative experiments on the ionosphere as well as the magnetosphere could then be performed. Diagnostic measurements of the trapped energetic electron fluxes may now be possible, using VLF signals transmitted from the ground. We have shown that the exponential growth rate can be obtained from a single pulse. If we accept the interaction model referenced here, the growth rate is a direct measure of the differential particle flux at the resonant velocity.

Another application of these experiments is in VLF communication. This experiment has shown that a sufficiently long coherent wave train can be amplified as much as 30 dB, a 3 order of magnitude increase in effective radiated power thus being given. It is of course necessary that the signal cross the equatorial plane to be amplified, the explanation given above being assumed. Thus a satellite transmitting to the ground in the northern hemisphere would have to be located in the southern hemisphere. It is also necessary to recognize that amplification has been observed so far only with ducted propagation. The properties of nonducted amplification remain to be investigated.

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