RADIOSCIENCE LABORATORY

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DEPARTMENT OF ELECTRICAL ENGINEERING
STANFORD UNIVERSITY · STANFORD, CA 94305

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STIMULATION OF ULF GEOMAGNETIC PULSATIONS BY CONTROLLED VLF TRANSMISSIONS INTO THE MAGNETOSPHERE

by

A. C. Fraser-Smith
R. A. Helliwell
T. F. Bell
T. L. Crystal
B. Dingle

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R. A. Helliwell
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In the VLF method, the basic stimulation frequency is the pulse repetition (or modulation) frequency, which is chosen to fall in the ULF range. Stimulation of ULF waves may also occur at any of the harmonics of this basic frequency, depending on the magnetospheric and ionospheric conditions at the time, or it may conceivably occur at a nonharmonic frequency if the conditions are particularly favorable and the generation process produces a high level of broadband ULF hydromagnetic noise.

Theoretical and experimental progress with the VLF method has been encouraging. Theoretical progress includes (1) computer simulation of the cyclotron resonance interaction, which is believed to play a key role in both the ULF generation mechanism and the amplification of VLF and ULF waves, (2) completion of a theory for ULF wave generation based on the repetitive precipitation of energetic electrons into the ionosphere by periodic VLF pulses from a ground-based transmitter, and (3) development of a method for computing the fluxes of energetic electrons precipitated by VLF waves in the magnetosphere.

Experimental progress includes the completion of several long-duration VLF transmission experiments using the 100 kW transmitter at Siple Station, Antarctica. Although it does not yet appear possible to stimulate ULF waves on demand using this VLF transmitter, our experiments suggest that VLF transmissions from Siple could alter the occurrences of Pc 1 pulsations at Roberval, Quebec, which is geomagnetically conjugate to Siple Station. Because the Pc 1 pulsation events that occur at Roberval can also probably be observed on many occasions over much of North America (and, by inference, over the equivalent conjugate area in the Southern Hemisphere), our experiments suggest that VLF transmissions into the magnetosphere from a single appropriately-located transmitter can influence ULF activity over a large area of the earth's surface. Thus, further experiments appear to be justified.

cont

Combining the theoretical and experimental results obtained during this research, it is suggested that naturally-occurring repetitive VLF activity can stimulate Pc 1 pulsation events, and it is further suggested that such VLF activity may be a major source of stimulation for Pc 1 pulsations. Thus, future experiments on ULF wave generation with ground-based VLF transmitters would probably benefit greatly if they were combined with a program of simultaneous observations of naturally-occurring VLF and ULF activity.

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Jerry Yarbrough provided all the Ubiquitous spectrum analyses used in the data analysis. This time-consuming effort is also gratefully acknowledged.

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Note: In this report we use the abbreviation ULF (ultra-low-frequencies) for frequencies less than 5 Hz. Pc 1 geomagnetic pulsations are observed in the upper part of this frequency range (0.2 to 5 Hz). ELF (extremely-low-frequencies) is used to designate frequencies in the range 5 Hz to 3 kHz, and VLF (very-low-frequencies) is used for frequencies in the range 3 to 30 kHz.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

In this report we present the results of a study of very-low-frequency (VLF; frequencies in the range 3 to 30 kHz) and ultra-low-frequency (ULF; frequencies less than 5 Hz) electromagnetic wave phenomena in the magnetosphere and ionosphere, with particular emphasis on the stimulation of ULF waves of class Pc 1 (0.2 to 5 Hz) by controlled VLF transmissions into the magnetosphere from large ground-based transmitters. Once generated in the magnetosphere or ionosphere, these ULF waves have the capability of propagating away from the generation region to large distances and, wherever they reach the lower ionosphere, producing ULF electric and magnetic field fluctuations on the earth's surface. Thus the waves could be used for long-range communication at a low date rate. In addition, since there is at present no known controlled artificial source of ULF waves in the ionized upper atmosphere, the waves could be used in active experiments that could answer some of the outstanding questions about the generation and propagation of the naturally-occurring ULF waves that produce Pc 1 geomagnetic pulsations. The reader is referred to the monograph of Jacobs (1970) for a complete description of the properties of these geomagnetic pulsations.

Although the ULF waves in the magnetosphere and ionosphere are basically electromagnetic waves, there is considerable interaction between electromagnetic and hydrodynamic phenomena at ULF in the ionized upper atmosphere, and the ULF waves that propagate in the magnetosphere and ionosphere have both electromagnetic and hydrodynamic properties. They are sometimes referred to as ULF magneto-hydrodynamic waves (Jacobs, 1970) or in abbreviated form as ULF hydromagnetic waves. We will use electromagnetic and hydromagnetic interchangeably when discussing ULF waves in the magnetosphere or ionosphere. In the largely nonconducting earth-ionosphere cavity, we need only be concerned with electromagnetic phenomena. However, the wavelength of ULF electromagnetic "waves" in this region is so large that any ULF magnetic or electric field observations are always made within a very small fraction of a wavelength from the source. The use of the term "wave" usually requires careful definition when this condition applies. In the present context we will only be marginally concerned with ULF field measurements in the earth-ionosphere cavity, and we will on occasion refer simply to the ULF electromagnetic phenomena observed on the ground as ULF waves.

The two major objectives of this study were (1) to develop a method to exploit the natural amplification properties of the magnetosphere at VLF and ULF to amplify man-made signals and, as discussed in the first paragraph, (2) to stimulate ULF waves of class Pc 1 (0.2 to 5 Hz) in the magnetosphere and ionosphere by injecting VLF waves into the magnetosphere from a ground-based transmitter. Encouraging progress was made during the course of the study toward achieving these objectives.

The study included three different theoretical efforts. The first of these efforts was an extension and expansion of past work at Stanford on VLF wave growth and emission triggering in the magnetosphere (VLF Wave Generation, Propagation, and Amplification Theory; Chapter II). Continuous development of this theory was essential if we were to have a detailed understanding of the many VLF wave-particle interaction effects in the magnetosphere. Once the VLF wave-particle interaction effects were understood, the new knowledge could be applied by analogy to ULF wave-particle interaction effects and, of course, both VLF and ULF wave-particle interactions play an important role in the theory of ULF stimulation by controlled VLF transmissions.

The second theoretical effort (VLF Theory Applied to ULF; Chapter III) involved the direct application of VLF theory and concepts to the case of ULF waves, and the third effort (ULF Generation Theory; Chapter IV) was in support of our experimental effort to stimulate ULF waves by controlled VLF transmissions. This latter effort provided two independent theoretical descriptions of ULF stimulation, which were indispensible for the planning of our ULF stimulation experiments.

In support of the ULF generation theory, calculations were made of the flux of electrons expected to be precipitated by a pulse of VLF waves. The results of these calculations are reported in Chapter V.

The results of several experiments to generate ULF pulsations by VLF transmissions from the ground-based transmitter at Siple Station, Antarctica, are described in Chapter VI. Also in Chapter VI, we describe a new generation mechanism for naturally-occurring Pc 1 geomagnetic pulsations: The stimulation of Pc 1 pulsations by natural periodic or quasi-periodic VLF activity. This generation mechanism is suggested by the results of our experiments to stimulate Pc 1 pulsations artificially. Finally, in Chapter VII, we present our conclusions and recommendations for further work.

This report is one of a pair whose common topic is the controlled artificial generation of ULF geomagnetic pulsations. The second report presents the results of a study of the "peninsula method" of generation, i.e., the use of the sea water around a peninsula as a ULF electric current loop to disturb the lower ionosphere and produce ULF hydromagnetic waves.

II. VLF WAVE GENERATION, PROPAGATION AND AMPLIFICATION THEORY

The starting point for our model of VLF wave generation in the magnetosphere was a suggestion by Brice (1963). He showed that VLF emissions could be explained in terms of transverse currents that resulted mainly from the phase bunching of near cyclotron resonance electrons by the longitudinal wave force $-eV_{\perp}B_{w\perp}\sin\theta$, where $-e$ is the electron charge, $V_{\perp}$ is the component of the electron's velocity perpendicular to the geomagnetic field, $B_{w\perp}$ is the component of the wave's magnetic field perpendicular to the geomagnetic field, and θ is the angle between $V_{\perp}$ and $B_{w\perp}$. The effect of the variable parameters (i.e., the inhomogeneity) of the magnetosphere on this model was treated by Helliwell (1967, 1970), who developed a criterion for the interaction length and showed that the interaction was relatively insensitive to $\dot{f}$/dt, i.e., the frequency slope of the generated signal. A simplified numerical simulation of the interaction was first performed by Helliwell and Crystal (1973), assuming a homogeneous model of the medium and a particle stream consisting of initially resonant electrons at a fixed pitch angle. This model showed pure exponential temporal growth of self-excited emissions, in agreement with observations, but it was too restricted to provide an interpretation of many other emission properties.

The next step, carried out under the subject contract, was to extend the distribution over a range of $v_{\parallel}$, the parallel velocity of the electrons, that was much larger than the trapping bandwidth. To accommodate the greatly increased number of calculations the NCAR CDC

7600 computer at Boulder, Colorado, was employed, using a remote access terminal at Stanford. For a homogeneous model and a flat distribution in $v_{\parallel}$, a phase-bunched transverse current parallel to $\bar{B}_w$ was produced for small bandwidth, as before, but its magnitude approached zero as the bandwidth was made large compared with the trapping bandwidth, just as predicted by linear theory. On the other hand, when a sloped $v_{\parallel}$ distribution was adopted, the current was perpendicular to $\bar{B}_w$, causing either growth or damping, depending on the sign of the slope. Furthermore, the magnitude of the current did not change when the $v_{\parallel}$ bandwidth was increased beyond the trapping bandwidth.

The effect of an inhomogeneity on the phase-bunched current for the flat $v_{\parallel}$ distribution was tested using a dipole magnetic field to represent the inhomogeneity. Again it was found that the current tended to zero as the $v_{\parallel}$ bandwidth increased, indicating that inhomogeneity cannot by itself create a transverse current. However the inhomogeneity can alter the phase and frequency of currents that already exist as a result of wave-induced phase bunching.

The next step was to introduce into the model the remaining wave perturbation forces. It was found that for certain model parameters the initial growth was negative (i.e., damping occurred), in agreement with linear theory. However for a sufficiently large slope in the $v_{\parallel}$ distribution, non-linear effects caused the growth rate eventually to become positive. The time required for this reversal in the sign of the growth rate to occur was surprisingly short (several msec).

The main result from these model studies is the finding that the actual stimulated currents may in fact derive their character from the fine-structure of the electron distribution function near resonance and near the middle (~45°) electron pitch angles (where the largest current components are formed). These predictions can be tested in future space experiments where both the waves and the electron distribution function can be measured simultaneously. They will also aid in understanding the phenomenon of triggered emissions. To summarize, the extended simulation model has given us a more complete, physical understanding of the wave-particle interaction. The full set of wave perturbation forces and a more general class of electron distribution functions have been included. Key results predicted by linear theory have been recovered and extended into nonlinear regimes. An important next step is to adapt the physical model and the computation scheme to the ULF case.

III. VLF THEORY APPLIED TO ULF

Detailed calculations of ULF refractive index surfaces were required as input both to ULF wave-particle interaction modelling and to ULF wave propagation analyses, including raytracing. These surfaces were found for cases including realistic minor-ion components. Especially important is the effect of cold helium, whose gyrofrequency, f_{He^+}, approximates the Pc 1 frequency range at relevant L shells. This ion modifies the ULF refractive index surface in two frequency regimes: (1) In a frequency "window" just below f_{He^+}, where the index surface tends to flatten out so that the associated ray paths are parallel to the earth's field. Thus signals at these frequencies should exhibit significantly more guiding than they would in the absence of the helium ions. Also, since these waves are slowed by the helium, the time available for energy exchange between the waves and nearly resonant protons is similarly increased, making emissions more likely at these frequencies. (2) Just above f_{He^+}, at frequencies between the 2-ion cutoff and the crossover frequency, where the refractive index surface is roughly circular rather than flat (as when helium ions are absent). Thus signals at these frequencies are strongly de-focused. Since waves at frequencies between f_{He^+} and the 2-ion cutoff are evanescent, magnetospheric ULF waves at frequencies above the equatorial f_{He^+} have less chance of being guided down to the ground.

The overall implication for the interaction model is that only a very narrow band of frequencies is available at the equator for the postulated interaction with the near resonant energetic proton population. This conclusion however is subject to the very restrictive assumption that the medium is slowly-varying; i.e., that the WKB approximation applies.

IV. ULF GENERATION THEORY

Two independent theories for the generation of Pc 1 geomagnetic pulsations (and possibly also including longer period pulsations) were developed during the course of our laboratory's research on ULF generation. Work on one of these theories was essentially completed before the commencement of the contract period covered by this report. This theory showed that it should be possible for two VLF waves to produce a ULF wave in the magnetosphere by means of a nonlinear interaction, and it was predicted that observable Pc 1 pulsations could be produced on the ground by two ground-launched VLF waves (Harker et al., 1974a, b). This theory provided guidance for our early experiments and the experiment reported by Willis and Davis (1976). However, as our experiments progressed it began to appear that the more appropriate theory for these experiments, which used a single VLF transmitter with limited modulation capability, was the theory being developed by Bell (1976).

The Bell (1976) theory is based on the experimental fact that significant and readily detectable fluxes of energetic electrons can be precipitated out of the magnetosphere by coherent VLF signals such as whistlers and VLF emissions. In these interactions the discrete signals appear to trigger a powerful natural instability in the energetic particle population, and the energy content of the precipitating particles is many orders of magnitude greater than the energy content of the triggering signal.

With the tremendous leverage available in an interaction of this kind, significant particle precipitation effects may be induced even by triggering signals of relatively low amplitude compared to typical VLF whistlers and emissions. In particular, it should be possible to trigger precipitation events by using a ground-based VLF transmitter. Bell (1976) therefore proposed the following mechanism for ULF generation: Periodic (period > 1/2 sec) transmissions from a VLF ground-based transmitter are used to trigger VLF emissions and precipitate energetic electrons (details of the calculation of the precipitated flux are presented in the following section). The periodic bursts of precipitated electrons modify the conductivity of the D and E regions of the ionosphere and induce periodic changes in current flow which in turn generate Pc 1 ULF waves. These waves are then amplified by the cyclotron resonance interaction discussed in Chapter II. Calculations indicate that ULF wave amplitudes of 1 γ may be produced by this process. Furthermore, steady state magnetic field fluctuations may reach 100 γ at ground level. Since both these amplitudes are readily measurable with present techniques, the results lend plausibility to the idea of attempting to produce detectable ULF waves using ground or satellite based VLF transmitters.

Although the work reported here was restricted to ground-based VLF transmitters, we note that the use of satellite-based VLF transmitters may be preferable for ULF generation since a satellite-based transmitter can operate close to the emission generation region near the equatorial plane and even at low power outputs can conceivably create a much larger flux of precipitated particles than a more powerful and distant ground-based transmitter.

Even at low altitudes a satellite-based VLF transmitter should still enjoy significant advantages over ground-based transmitters in experiments to precipitate energetic particles. For example, a substantial portion of the radiation from a ground transmitter is lost in the earth-ionosphere waveguide and does not enter the magnetosphere. Thus the satellite transmitter would make more efficient use of the available power. Furthermore, the satellite transmitter can stimulate a much wider range of wave normal angles in the magnetosphere than can a ground-based transmitter. This capability significantly expands the options available for maximizing the precipitated flux.

V. PRECIPITATED FLUX CALCULATIONS

The intensities and spectral shapes of the fluxes of energetic electrons precipitated by the various discrete VLF wave forms that appear in the magnetosphere (i.e., VLF whistlers, emissions, transmitter pulses) can now be calculated. This is achieved using a model that is based on ducted propagation of a short, monochromatic, constant-amplitude wave pulse and that assumes a sharply-bounded loss cone for the trapped energetic electron flux. By using small-signal approximations an easily-evaluated analytical solution for the precipitated flux is obtained. A simple test indicates where the approximations fail. It appears that the calculations are adequate for most practical problems, since uncertainties in the data are usually greater than uncertainties in computation.

The precipitated flux is calculated from the expression $I_t = \sigma B_w j_{oc}$, where I_t is the precipitated differential flux crossing a plane perpendicular to the static magnetic field lines at the effective top of the dense atmosphere (i.e., at a height of about 100 km), B_w is the (peak) amplitude of the oscillating magnetic field of the magnetospheric wave, and j_{oc} is the directional differential trapped flux at the edge of the loss cone. Note that I_t is proportional to both B_w and j_{oc}, and that j_{oc} is generally a decreasing function of the electron energy E. The proportionality factor σ is also a function of energy and further depends on the parameters L, n_0, and f, i.e., on the L value of the field line along which the waves and electrons are travelling, the thermal plasma density n_0 at the equatorial position on that field line, and the nominal wave frequency f. Further details are given in the paper by Dingle (1977).

As an example, consider the case where (L, n_o, f) have the values $(4.2, 500\ \mathrm{cm}^{-3}, 5\ \mathrm{kHz})$. This represents quiet conditions within the plasmapause on the Siple-Roberval field line (see Helliwell and Katsufrakis, 1974) at a frequency just below half the equatorial gyrofrequency where amplification and generation of emissions are likely to occur (Carpenter and Miller, 1976). Figure 1 illustrates the energy dependence of σ for this example. Arrows indicate minimum energies for applicability of the simple calculation at three levels of wave amplitude (i.e., B_w). An assumed representative spectrum for the trapped flux at energies greater than 40 keV under quiet conditions near L = 4.2 is $j_{oc} = 10^{10}\beta^{-1}E^{-10/3}$, where E is measured in keV (Lyons and Williams, 1975), and where β is the ratio of the measured flux to the flux at the edge of the loss cone (assumed independent of energy). Noting that σ is well approximated above 1 keV by $\sigma = 0.03\ E^{-2/3}\mathrm{sr/m\gamma}$, and taking reasonable values $B_w = 10\ \mathrm{m\gamma}$ and $\beta = 10$, the integrals $\int I_t\, dE$ and $\int EI_t\, dE$ are easily evaluated for the energy range above 40 keV and are found to be about 2000 electrons/cm^{2}s and 2×10^{-4} erg/cm^{2}s, respectively. Fluxes of this magnitude, if widespread, can significantly affect the phase of VLF signals (Potemra and Rosenberg, 1973) and should be large enough to produce amplitude perturbations of the type observed by Helliwell et al. (1973) and Dingle and Carpenter (1976). With post-storm or substorm trapped flux levels and more optimal wave and medium parameters, the precipitated flux can be increased two orders of magnitude or more.

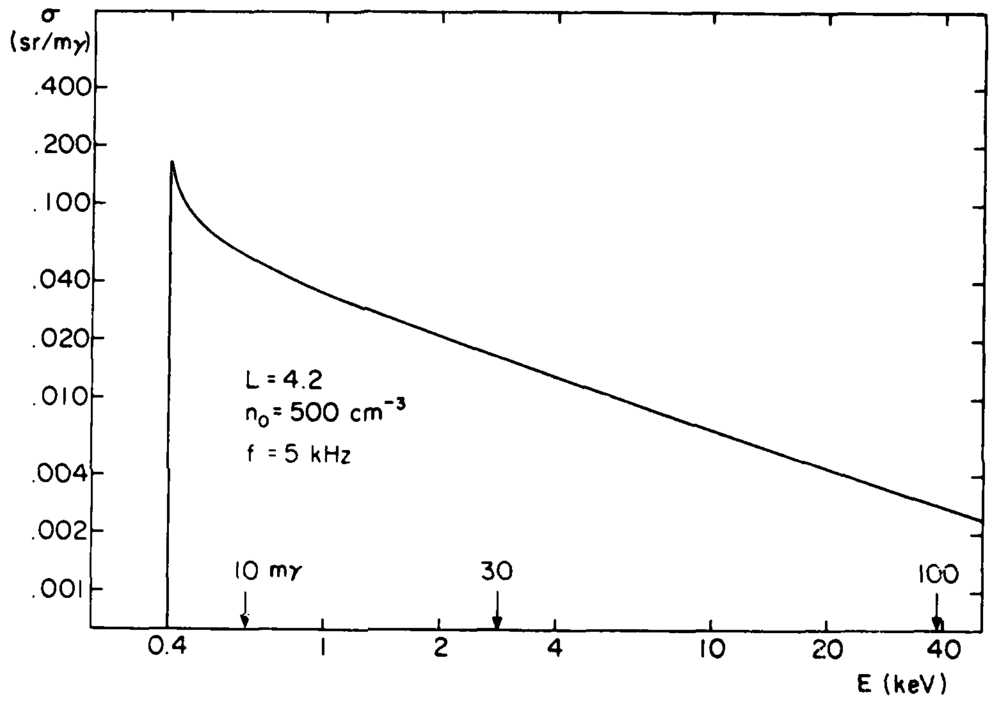

Figure 1. Variation of the precipitation function σ with electron energy E.

VI. EXPERIMENTAL RESULTS

1. Initial Results

In Chapter IV we discussed two (theoretical) methods for the generation of ULF geomagnetic pulsations by VLF transmissions into the magnetosphere. The two generation mechanism are distinct, one being based on a wave-particle interaction (Bell, 1976) and the other on a nonlinear wave-wave interaction (Harker et al., 1974a, b). For several years prior to the publication of these theoretical mechanisms it had been thought that powerful modulated, or pulsed, VLF transmissions into the magnetosphere could be capable of generating ULF signals. In 1973, stimulated by these developing ideas, we initiated a series of experiments on ULF pulsation generation using VLF transmissions, and these experiments and the resulting data analysis and comparison with theory continued through February 1977. The experiments were all conducted with the 100 kW VLF transmitter located at Siple Station, Antarctica, and with a ULF recording system located at Roberval, Quebec, conjugate to Siple Station. A full description of the VLF transmitter is given by Helliwell and Katsufrakis (1974). An important feature of the VLF transmitter/ULF receiver pair was its optimum position relative to the plasmapause: the VLF transmitter and ULF receiver lay on opposite ends of the L = 4 field line, which marks the average position of the plasmapause. Thus, over an interval of several months, the natural wave and particle conditions along the field line linking the VLF transmitter and ULF receiver varied widely. Although this variability necessitated considerable data processing, it enabled us to thoroughly test particular ULF wave generation mechanisms.

Initial results of our experiments were reported by Fraser-Smith and Cole (1975). These results were encouraging. A series of frequency-shift-keyed (FSK) transmissions from Siple Station were made for 8 hours each day during the interval September 1-7, 1973, with pulse lengths in the range 200 ms to 3.2 s (i.e., pulse frequencies in the range 5 Hz to 0.31 Hz). The same transmission schedule was followed each day. It was described in detail by Fraser-Smith and Cole (1975), and it consisted primarily of intervals of FSK transmission interspersed with intervals of no transmission. The principal results of this experiment were the observations that (1) all Roberval ULF pulsation events with frequencies in the Pc 1 range that started during the 8 hour transmission periods had start times within an interval of FSK transmission, and (2) the average rate of occurrence of the ULF activity during the 8 hour transmission periods was about twice the rate observed during the same period on days with no transmissions.

Although these initial experimental results were encouraging, there were some puzzling features of the data. First, the spectral characteristics of the Pc 1 events (including their average frequency) appeared to be independent of the VLF transmissions. There were, in particular, no narrow-band Pc 1 signals with center frequencies at any of the pulse frequencies of the VLF transmissions. Second, there was no apparent 1:1 relation between the commencement of an interval of pulsed VLF transmission and the start of a Pc 1 event. The start times of the Pc 1 pulsation events were approximately uniformly distributed throughout the intervals of VLF transmission. Thus, the results of this initial experiment suggested that pulsed VLF transmissions could stimulate Pc 1 pulsation events and order their occurrence, but, at least in the transmission format that was used in the experiment, they were ineffective for producing a particular kind of Pc 1 signal on demand. Further experiments were clearly required to determine the effectiveness of a variety of VLF transmission formats for Pc 1 pulsation stimulation.

2. Subsequent Experimental Results

Further ULF generation experiments with the Siple Station VLF transmitter/Roberval ULF receiver pair were conducted during the following intervals:

Second Experiment:	August 16-20, 1974
Third Experiment:	March 17-April 17, 1975
Fourth Experiment:	August 4-October 27, 1975

The VLF transmitter was "mothballed" at the end of December 1975, in preparation for summer closure of the station. For logistic reasons, the station was not reopened until late in 1976, toward the end of our research contract, and we were therefore unable to conduct further experiments on ULF generation with the VLF transmitter. However, by taking advantage of the information derived from the previous series of experiments, we were able to make an extensive study of ULF signal stimulation by naturally occurring VLF whistlers and emissions during 1976. This latter study complemented our active experiment work with the VLF transmitter and provided important new evidence for ULF stimulation by periodic VLF signals.

2.1 Experiment of August 1974. The transmission program for the second experiment was essentially the same as for the first (September

1-7, 1973) except for minor modifications. Transmissions at 14 kHz, 16 kHz, or other high VLF frequencies were not used because of the low transmitter/antenna efficiency at those frequencies [maximum efficiency of the Siple antenna occurs at approximately 10 kHz; ideal matching between the transmitter and antenna occurs only in the frequency range 4 to 8 kHz (Raghuram et al., 1974)]. Also, the nominal equatorial electron gyrofrequency for the L = 4 field line is 13.8 kHz, and it was thought that transmission frequencies closer to half the equatorial gyrofrequency would be more suitable for ULF generation (waves travelling up a field line with frequencies greater than half the equatorial electron gyrofrequency usually do not reach the equatorial point: they cease to be guided once they reach a point where their frequency is equal to half the local electron gyrofrequency). Thus, FSK frequencies of 3.5 and 4.5 kHz were used in the second experiment. Furthermore, only three FSK modulation pulse lengths were transmitted. Each pulse length was transmitted over an entire half-hour period, and the three were cycled over the transmission period. Compared with the previous series, the start of the daily transmission schedule was moved back by three hours so that the transmissions started at 0800 UT and ended at 1530 UT. The resulting schedule is shown in Table 1.

The first three days of the scheduled 5-day experiment were geomagnetically quiet (Ap < 10), and considerable well-defined Pc 1 pulsation activity was observed, most of it within the 8-hour VLF transmission interval. However, a moderately strong magnetic storm commenced on the fourth day (August 19), and Pc 1 pulsation activity was effectively blanked out on the fourth and fifth days of the

Table 1. Daily Transmission Schedule, August 16-20, 1974

Hour UT	FSK pulse length (m sec)
0800 - 0830	400
0900 - 0930	800
1000 - 1030	1600
1100 - 1130	400
1200 - 1230	800
1300 - 1330	1600
1400 - 1430	400
1500 - 1530	800

Note: Powers used were 25 kW at 4.5 kHz and 17.5 kW at 3.5 Hz. There were no transmissions in the second half-hour of each hourly interval.

experiment (Ap was 40 and 46 on August 19 and 20, respectively). The comparatively small 3-day sample of Pc 1 data was judged inadequate for statistical studies, but spectrograms of the Pc 1 activity, which exhibited numerous narrow frequency bands and other interesting frequency structure, were examined in detail.

The most extraordinary event of the three-day sample occurred during the interval 1300-1630 UT on August 16. It had an extremely narrow-band component with a frequency of approximately 0.84 Hz that lasted for almost thirty minutes. This "tone" started at a frequency of 0.85 Hz and gradually drifted lower in frequency, ending at 0.83 Hz. It started during the interval 1500-1530 UT, when the FSK pulse length was 800 m sec. Although consideration was given to a variety of possible stimulation modes, it was found impossible to relate the frequencies of this "tone" to the pulse frequency of the VLF transmission.

Another unusual characteristic of the Pc 1 event was a suggestion of chevron frequency structure, i.e., a series of periodic or nearly periodic elements in the spectrogram of the event, with each element consisting of a chevron-shaped combination of rising and falling tones. This observation ultimately led to a search for better-defined examples of the new variety of fine structure and the publication of a brief study of their characteristics (Fraser-Smith, 1977a). The chevron structure occurs naturally in Pc 1 geomagnetic pulsation events, and thus its occurrence during the August 16, 1974, event was probably unrelated to the VLF transmissions taking place at the time.

Although this second experiment gave interesting results, it did not provide enough data to assist our study of ULF geomagnetic stimulation by pulsed VLF transmissions. Thus, in later experiments we greatly increased the number of days during which VLF transmissions were made for ULF stimulation.

2.2 Experiment of March-April 1975. A number of major changes were made in the VLF transmission format for this experiment. These changes were made largely to provide the most favorable possible conditions for ULF wave generation by the Bell (1976) mechanism. It was decided that the possibility of ULF generation would be substantially enhanced if the VLF transmission frequency could be adjusted throughout the experiment so that it was always close to the frequency (if any) at which natural triggering of VLF emissions was occurring. A Rayspan spectrum analyzer had been installed at Siple Station over the 1974-75 austral summer, and is was possible for the station operators to monitor the spectrum of natural VLF activity before and after transmitter operation. Observations at the conjugate point (Roberval) had shown that natural triggering occurred most often in the frequency range 5 to 7 kHz, corresponding approximately to the frequency range $(0.4\text{-}0.5)f_{eq}$, where f_{eq} is the equatorial electron gyrofrequency. Thus, the transmitter frequency was specified to be in the range 5.4 to 5.9 kHz unless natural triggering was observed to occur at a frequency outside this range, in which case the transmitter frequency was to be moved to the triggering frequency. To assist the station operators to observe the natural VLF background on the Rayspan, no VLF transmissions were made for the last ten minutes of each hour during the transmission interval.

Another change in the transmissions was the elimination of the two-frequency FSK mode of operation, and conversion to a single-frequency/idler mode. Specifically, single-frequency 0.5 second pulses were transmitted every second, with an "idler" waveform inserted during the remaining 0.5 second. The idler waveform consisted of alternating 50 ms FSK pulses at 400 and 500 Hz below the main 0.5 second VLF pulse frequency. Previous experiments had shown that the idler mode was ineffective for triggering VLF emissions. Thus the overall transmission sequence was designed to give minimum triggering during one half of the one second modulation period and maximum triggering during the other half (through selection of the VLF frequency). It was hoped that the resulting strong 1 Hz amplitude modulation of triggered VLF emissions would produce a corresponding modulation of electron precipitation into the ionosphere and thus produce geomagnetic pulsations with frequencies near 1 Hz according to the Bell mechanism.

To maximize the sensitivity of the experiment, VLF transmissions were made only on alternate days. Measurements of the natural background of ULF activity on the days when there were no VLF transmissions provided essential control data for subsequent statistical analysis. The transmissions program for ULF generation was started on March 17 and ended on April 17, 1975, and the transmissions were made during the 9-hour interval 0800-1700 UT. Except for the hour 1200-1300 UT, the program for each hour was the same: the same basic five-minute segment transmitted for the first 50 minutes and no transmissions for the last 10 minutes. The basic five-minute segment consisted of the 0.5 second single-frequency VLF pulse plus 0.5 second idler mode for the first four minutes and 50 seconds, followed by a ten second staircase sequence. For the hour 1200 to 1300 UT, the program was identical to the program for other hours except for the first 20 minutes when a variable series of VLF transmissions was employed in support of the ongoing VLF research. It can be seen that the transmissions consisted almost entirely of the single frequency/idler mode for ULF generation.

Helicorder charts and magnetic tape recordings gave complete coverage of Pc 1 pulsation activity at Roberval during the experiment. The magnetic tapes were analyzed with an Ubiquitous spectrum analyzer and the number of 15-minute intervals of Pc 1 pulsation activity were derived for each hour--both for the 16 days with transmissions and for the 15 days without. In cases where the magnetic tape records were incomplete the 15-minute intervals were derived from the Helicorder charts. These data were then used to prepare the histograms of daily

Pc 1 pulsation activity for days with and without transmissions shown in Figure 2.

There were some noticeable differences in activity over a few hourly intervals (e.g., 03-04 UT; 12-13 UT; and 21-24 UT), but on the whole there was little difference between the two distributions. A chi-square test confirmed that there was no statistical difference (χ^2 = 25.8, with a probability in the range 0.2 to 0.8 that the frequency distribution for the days with VLF transmissions is just a chance variation of the distribution for the days without transmissions).

Comparing the total number of 15-minute intervals with Pc 1 activity observed during the 16 days containing VLF transmissions (382) with the total number observed during the 15 days without transmissions (389), there was an indication that our transmission program not only did not stimulate Pc 1 pulsations but actually produced a small reduction of Pc 1 activity during the days with VLF transmissions. Further evidence for a lack of ULF stimulation was provided by a comparison of the total number of 15-minute intervals of Pc 1 activity occurring in the first 15 minutes of the hours 0800-1700 UT with the number occurring in the last 15 minutes. For the 16 days with VLF transmissions the number of 15-minute intervals was 41 for the first 15-minutes, and 43 for the last 15-minutes; for the 15 days without transmissions the corresponding figures were 44 and 46, respectively. These data indicate that the recommencement of the VLF transmitter program at the start of each hour in the interval 0800-1700 UT did not stimulate any extra Pc 1 pulsation activity.

Finally, each day during the experiment was classified either as poor, fair, or good according to the quantity of VLF emission activity. There were five days with good VLF emission activity that also had VLF transmissions. The total number of 15-minute intervals of Pc 1 pulsation activity for these five days was 188, which implies substantial Pc 1 pulsation activity. At the same rate of occurrence, the total number of 15-minute intervals for 16 days would be 601. This figure, when compared with the total number of 382 intervals that was actually observed for the 16 days with transmissions, suggested that Pc 1 pulsation activity on days with both VLF transmissions and good VLF emission characteristics was substantially greater than on days either with VLF transmissions and poor VLF emission characteristics or with no VLF transmissions.

Taken as a whole, the results of the March-April 1975, ULF generation experiment were disappointing. However, the experiment provided definite information about the suitability of a particular transmission program. Thus, considering the general lack of information on the effectiveness of possible transmission programs, the experiment was not unsuccessful.

After the examination of the transmission program, it was decided to remove the restriction to a 1 Hz ULF generation frequency and to make several other modifications. However, because of the apparent effectiveness of the original program during times of good VLF emission activity, large changes in the program were avoided. These modifications led to the more successful ULF generation experiment during the interval August 4-October 27, 1975.

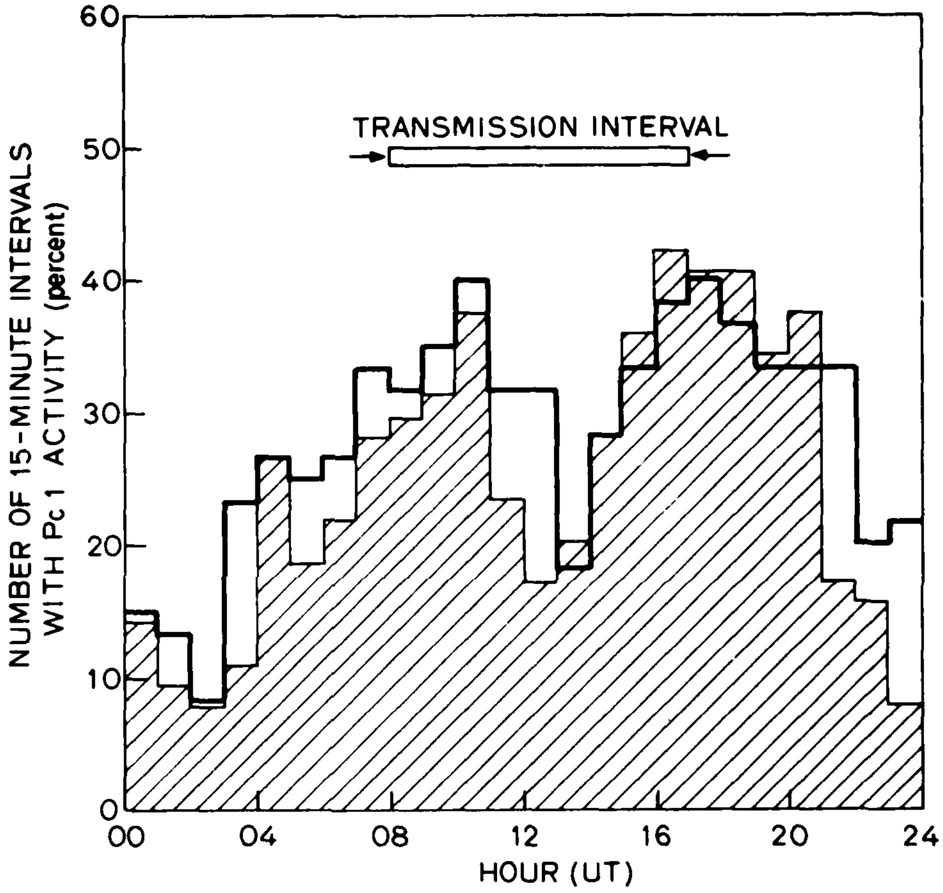

Figure 2. Comparison of the number of 15-minute intervals with Pc 1 pulsation activity recorded at Roberval on days with (shaded) and without (solid line) VLF transmissions from Siple Station. The data were derived during the interval March 17 to April 17, 1975. During this interval there were 16 days with VLF transmissions and 15 days without.

2.3 Experiment of August-October 1975. The most important modification made to our VLF transmission program for this new experiment was a lowering of the basic VLF pulse repetition frequency from 1.0 to 0.2 Hz. Hz. This modification was made for two reasons. Primarily, it was made to provide more opportunities for ULF generation from a single VLF transmission program. With a 0.2 Hz fundamental frequency (which,, incidentally, is the lowest frequency in the Pc 1 pulsation frequency range), significant energy would also be present for ULF generation at the odd harmonics 0.6, 1.0, 1.4, ..., Hz. Depending on the form of the triggered VLF emissions, if any, energy could also possibly be present at the even harmonics 0.4, 0.8, 0.2, ..., Hz. This modification was largely stimulated by the work of Willis and Davis (1976), who, in an independent ULF generation experiment using the high-powered U.S. Navy VLF transmitter at Cutler, Maine, had observed instances of Pc 1 pulsation events apparently initiated at the odd harmonics of a 0.2 Hz fundamental modulation frequency. The second reason for choosing the lower repetition frequency was to avoid echo-induced suppression of the transmitted VLF signals (Raghuram et al., 1977).

Another modification to the VLF transmission program for ULF generation was to divide it into two subprograms. The first of the ("ULF-pulse") consisted of the pulse-idler sequence used in the previous experiment with the pulse repetition frequency changed to 0.2 Hz. Specifically, the ULF-phase subprogram consisted of a sequence of 1 second CW VLF pulses at the base frequency followed by four seconds of the 50 msec idler mode. The second subprogram ("ULF-ramp") consisted of a sequence of 3-second long VLF ramps, where the VLF frequency increased linearly from 1 kHz below the base frequency up to the base frequency over an interval of three seconds, followed by two seconds of the 50 msec idler mode. The object of transmitting the VLF ramps was to ensure that the best VLF triggering frequency would be matched at least once every five seconds by the transmitter frequency.

Each hour of the VLF transmission program for ULF generation contained four 4 m intervals of transmission of the subprograms as follows: ULF ramp, 01 to 05 m, 06 to 10 m, 11 to 15 m, 16 to 20 m; ULF-pulse, 31 to 36 m, 36 to 40 m, 41 to 45 m, 46 to 50 m. The transmitter was off for the first minute of every five for VLF synoptic recordings, and also for the two 10 m intervals 20 to 30 m, and 50 to 60 m for observation of the natural VLF activity at Siple and returning of the transmitter to the optimum triggering frequency.

To permit the continuation of independent research on the triggering of VLF emissions and other VLF transmission phenomena, the ULF generation program was transmitted for only part of each day. The transmission program for each day consisted of a repetition of a basic three hour sequence consisting of one hour of the ULF generation program followed by two hours of a general VLF research program designated "Univ 3." Transmission were made for five days each week, with the basic three hour sequence repeated three times a day on days 1 and 3, and twice on days 2, 4, and 5. The hours of transmission varied each day of the week according to the following schedule:

1. Early Series (August 4 to September 26, 1975)

Day 1	0800 to 1700 UT	9 hours
2	0800 to 1400 UT	6 hours
3	0800 to 1700 UT	9 hours
4	1100 to 1700 UT	6 hours
5	0800 to 1400 UT	6 hours

2. Late Series (September 29 to October 27, 1975)

Day 1	1400 to 2300 UT	9 hours
2	1400 to 2000 UT	6 hours
3	1400 to 2300 UT	9 hours
4	1700 to 2300 UT	6 hours
5	1400 to 2000 UT	6 hours

The basic VLF frequency used in the transmission was nominally between 4.9 and 5.9 kHz. However, the frequency was changed regularly to coincide with the natural VLF triggering frequency (if any) observed in real time at Siple, and it could therefore be outside its nominal range on occasion. One exception to this rule occurred on day 5 when the basic frequency was fixed in the range 14 to 15 kHz during the ULF-pulse subprogram.

The statistical results of this experiment are summarized in Figures 3 and 4. In the first of these figures the results apply to the early part of the experiment (i.e., August 4 to September 26, 1975), where the transmission started mostly at 0800 UT and ended mostly at 1700 UT. In the second figure the results apply to the later part of the experiment (i.e., September 29 to October 27, 1975), where the transmission started mostly at 1400 UT and ended mostly at 2300 UT. In both figures the transmission interval is indicated by a solid horizontal line in one of the upper panels.

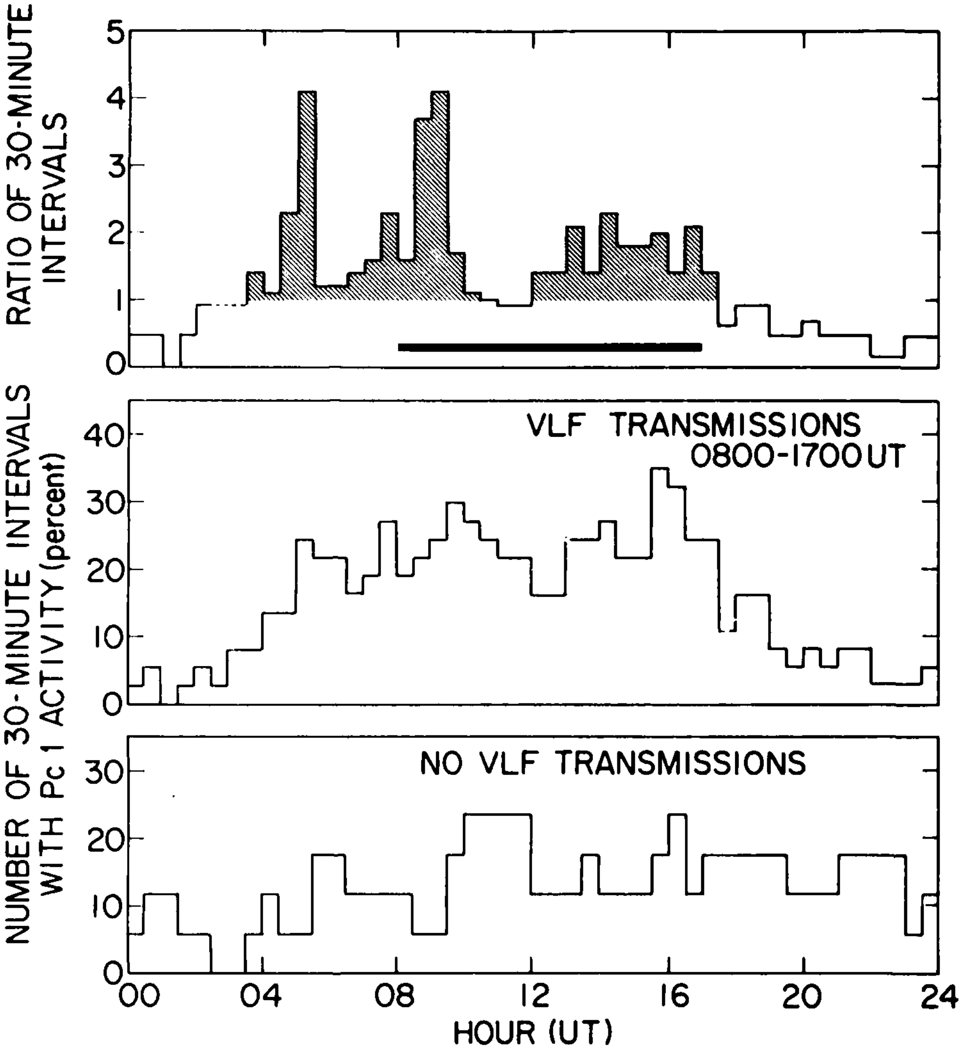

Figure 3. Comparison of the number of 30-minute intervals with Pc 1 pulsation activity recorded at Roberval on days with and without VLF transmissions from Siple Station. These data were obtained during the interval August 4 to September 26, 1975. During this interval there were 38 days with VLF transmissions and 16 days without. The transmission interval (0800-1700 UT) is indicated in the top panel by a solid horizontal line.

There were 38 days with transmissions during the early part of the experiment and 16 days without (two of the scheduled transmission days had no transmissions), and, as shown by Figure 3, there was a significant difference in the ULF activity observed on the two classes of days. The middle and bottom panels in the figure show the variation of activity over a 24 hour UT day, and it can be seen that the variation for the days with VLF transmissions peaks during the transmission interval, whereas the variation for the days with no VLF transmission shows little evidence of any trend. The two variations are further compared in the top panel, which shows the ratio of the number of 30-minute intervals in the two lower panels. If the VLF transmissions had no effect on ULF activity, the ratio would be expected to have an average close to one. However, as can be seen, the ratio is mostly larger than unity throughout the transmission interval, and for some hourly intervals it is substantially greater than unity. Also noteworthy is the increase of the ratio before the transmission interval, i.e., from 0400 to 0700 UT. This increase must be a residual effect from VLF transmissions on the previous day. Any such residual effect would be most apparent in the data for days with VLF transmissions (approximately 80% of days with VLF transmissions were preceded by another day with VLF transmission, whereas only about 50% of days without VLF transmissions were preceded by a day with transmissions).

The implication that VLF transmissions on the one day can affect ULF activity on a following day is one of the more interesting results to come out of this series, and there is further evidence for such an effect in Figure 3. Comparing the diurnal variation on days with VLF transmissions shown in Figure 3 with the two variations (days with and without VLF transmissions) shown in Figure 2, we see considerable similarity, even to the common dip in activity near 1200 UT. A roughly similar diurnal variation was observed earlier by Fraser-Smith and Cole (1975) for seven consecutive days with VLF transmissions. However, no such diurnal variation is observed in Figure 3 for the days without VLF transmissions. Unlike the days without VLF transmissions during the March-April 1975 experiment (Figure 2) which alternated with days containing VLF transmissions, the days without VLF transmissions in the September-October 1975 experiment were weekend days, i.e., two adjacent days without VLF transmissions. Assuming there was no strong "weekend effect" involved in this case (Fraser-Smith, 1977b), the lack of a well-defined diurnal variation for the data in the bottom panel of Figure 3 may be caused by the mixing of days immediately preceded by a day with VLF transmissions with days not immediately preceded by VLF transmissions.

In addition to the increase in Pc 1 pulsation activity in the interval 0400-0700 UT that is evident in the top panel of Figure 3, there is also a general decrease of activity immediately following the VLF transmissions. This change is probably related to VLF transmission-induced changes in the energetic proton population in the magnetosphere near L = 4.

The statistical results for the later part of the experiment (September 29 to October 27, 1975) are quite different from those obtained during the earlier part. There were 19 days with transmissions and 10 days without in this later part of the experiment (two of the scheduled transmission days had no transmissions), and, as shown by the data in Figure 4, VLF transmissions in the interval 1400 through 2300 UT do not produce an increase in Pc 1 pulsation activity on days with VLF transmissions as compared with the activity on the days without VLF transmissions.

Comparing the data in the two lower panels of Figure 4 with the data in the two lower panels of Figure 3, it appears that the predominant effect of the late transmissions interval is to produce a diurnal variation lacking any well-defined trend.

We conclude from this part of the experiment that the time of day during which VLF transmissions for Pc 1 pulsation generation are made can have an important effect on the pulsation activity subsequently observed. Combining the results of all the experiments, including the results reported by Fraser-Smith and Cole (1975), it appears that VLF transmissions from Siple during the interval 0500 to 1700 UT may be more effective for ULF generation at Roberval than the same transmissions in the interval 1400 to 2300 UT.

3. Stimulation of Individual Pc 1 Pulsation Events

In addition to the compilation of the statistical data summarized in Figures 2 through 4, spectrograms of the ULF and VLF data recorded at Roberval during each experiment were examined for evidence of 1:1 stimulation of particular Pc 1 pulsation events by particular intervals of VLF transmissions. Many examples of possible 1:1 stimulation were found, and several of these examples were examined in detail. Expanded spectrograms of the ULF data were prepared, and the start times of the Pc 1 pulsation events were measured as accurately as possible. Expanded

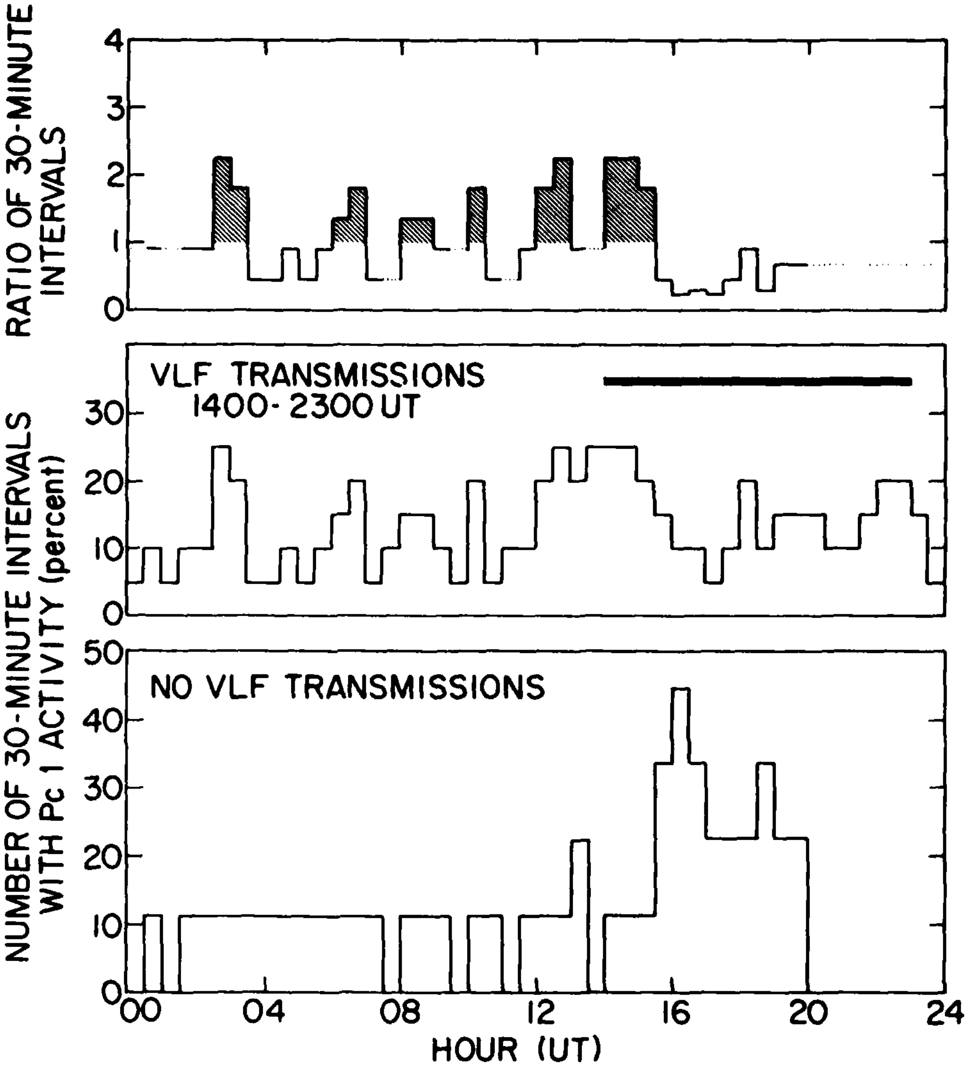

Figure 4. Comparison of the number of 30-minute intervals with Pc 1 pulsation activity recorded at Roberval on days with and without VLF transmissions from Siple Station. These data were obtained during the interval September 29 to October 27, 1975. During this interval there were 19 days with VLF transmissions and 10 days without. The transmission interval (1400-2300 UT) is indicated in the middle panel by a solid horizontal line.

spectrograms of the VLF activity just before, during, and after these start times were also prepared, and the characteristics of the ULF and VLF signals were intercompared. Particular attention was given to the starting frequencies of the Pc 1 pulsation events, and the possible existence of a relation between these frequencies and the pulse repetition frequencies of the VLF transmissions.

In the examples examined there were many indications of a relation between the VLF transmissions and the Pc 1 pulsation events. However, in all cases there were also enough differences between the characteristics of the ULF and VLF signals for us to remain doubtful about the existence of a direct relation between the VLF transmissions and the subsequent Pc 1 pulsation events. We concluded that there was evidence for 1:1 stimulation of Pc 1 events by the VLF transmissions, but that further work would be required to establish the details of the stimulation process.

A good example of a Pc 1 pulsation event that was possibly stimulated by VLF transmissions is shown in Figure 5. In this figure, the top panel shows a spectrogram of Pc 1 pulsation activity recorded at Roberval during the approximate interval 1045-1330 UT on September 1, 1975. There were VLF transmissions from Siple Station during this interval, as described in Chapter VI, Section 2.3. The start time of the Pc 1 pulsation event that occurred during the interval is estimated at 1133.8 ± 0.5 UT, and it is indicated on the time axis by a small triangle. A spectrogram of the VLF activity recorded at Roberval during the 10-minute interval 1128-1138 UT containing the start time of the Pc 1 pulsation event is shown in the middle panel.

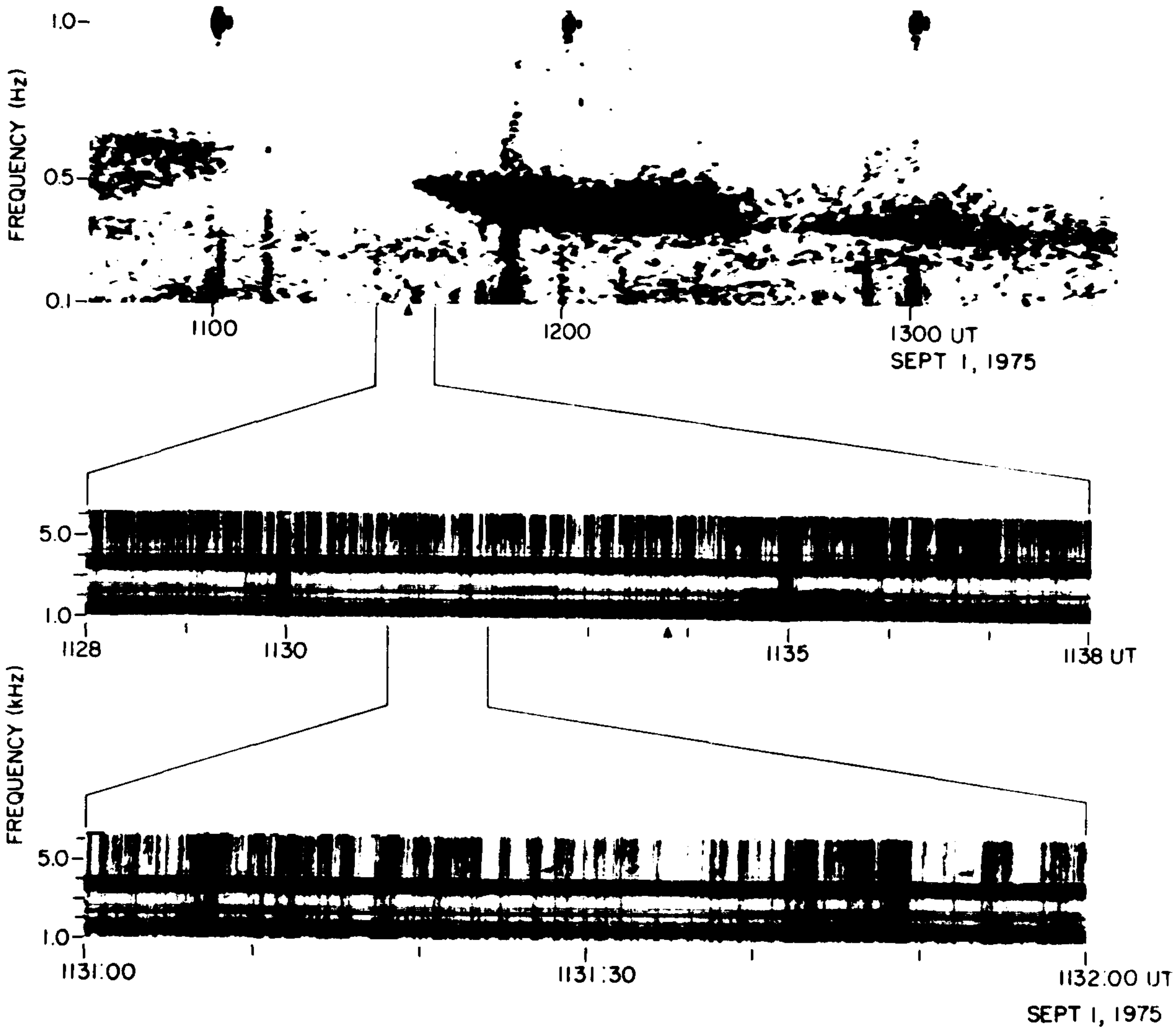

Figure 5. Spectrograms of North-South ULF and VLF data recorded at Roberval during the interval 1045 through 1330 UT on September 1, 1975. The top panel shows a Pc 1 pulsation event starting at (1133.8 ± 0.5) UT, and the two lower panels show the simultaneous VLF activity occurring around this time.

Following a 10-minute break, the VLF transmissions from the Siple transmitter recommenced at 1130 UT. The transmission format at this time consisted of 1 second CW VLF pulses at a frequency of 4.5 kHz followed by four seconds of the 50 msec idler mode at a center frequency of 3.5 kHz. As can be seen on the figure, the transmissions could immediately be detected at Roberval following their ecommencement (middle panel). Furthermore, as shown by the bottom panel, the transmissions were triggering emissions. After about three minutes the transmitted signals began to weaken, and they disappeared soon after 1134 UT. Following a brief reappearance in the interval 1136 to 1137 UT, the signals disappeared completely and did not reappear again.

This particular combination of VLF and ULF signals has several interesting features. First, an interval of good field line transmission of the VLF pulses preceded the appearance of the Pc 1 pulsation event, and second, the magnetospheric conditions and VLF transmitter frequency were suitable for triggering of VLF emissions by the transmitted pulses. Thus, the VLF conditions should have been ideal for the mode of Pc 1 pulsation stimulation proposed by Bell (1976). Third, a delay of a minute or more in the appearance of a Pc 1 pulsation event following stimulation is to be expected, based on the velocities of propagation of the hydromagnetic waves producing the Pc 1 pulsation event (e.g., Kenney and Knaflich, 1967), and the possible need for amplification before the waves can be detected on the ground. The first appearance of the Pc 1 pulsation event in Figure 4 at 1133.8.UT, at a time when the transmitted VLF signals are weakening at Roberval, is consistent with stimulation in the interval 1130-1133 UT, when the transmitted VLF signals are strongest at Roberval. Finally, it will be noted that the starting frequency of the Pc 1 pulsation event is (0.49 ± 0.02) Hz, which does not correspond to a harmonic of the VLF pulse repetition frequency (0.2 Hz). It is largely for this latter reason that we do not definitely attribute the occurrence of the Pc 1 pulsation event to stimulation by the Siple VLF transmitter. Fraser-Smith and Cole (1975) had previously noted that no narrow band Pc 1 signals were observed at the pulse frequency of the VLF waves. Our lack of observations of Pc 1 pulsation events occurring at harmonics of the pulse repetition frequency extends these earlier observations. The result does not necessarily contradict the observation by Willis and Davis (1976) of a relationship between the pulse repetition frequency and the starting frequency of Pc 1 pulsation signals. The latter experimenters used a VLF transmitter that was perhaps an order of magnitude more powerful (radiated power) than the Siple transmitter: with such a powerful transmitter it may be possible to force the starting frequency of a stimulated Pc 1 pulsation event to conform to the VLF pulse repetition frequency. It may be noted that in Figure 5, the center frequency of the Pc 1 pulsation event decreases during the transmission interval until it is close to 0.4 Hz, i.e., the second harmonic of the VLF pulse repetition frequency.

4. Stimulation of Pc 1 Geomagnetic Pulsations by Natural VLF Activity

Several different mechanisms have been suggested for the natural stimulation of Pc 1 geomagnetic pulsation events. These mechanisms include hydromagnetic noise in the magnetosphere (Jacobs and Watanabe, 1966), bursts of electromagnetic radiation from high-energy charged particles (Jacobs and Watanabe, 1966), or sferics from lightning discharges (Fraser-Smith and Roxburgh, 1969). Guided by the results of our experiments to generate Pc 1 pulsations by VLF transmissions into the magnetosphere, two of the authors proposed a new mechanism: the stimulation of Pc 1 pulsation events by naturally-occurring repetitive VLF signals (Fraser-Smith and Helliwell, 1976). The VLF signals may be echoing whistlers, periodic chorus elements, or other periodic or quasi-periodic VLF wave-trains echoing along a geomagnetic field line. It is hypothesized that the VLF wave trains induce repetitive precipitation of energetic electrons into the ionosphere and that this precipitation produces hydromagnetic waves (at the VLF repetition frequency and its harmonics) on the geomagnetic field line along which the VLF wave trains are propagating, and on adjacent field lines. Provided the conditions are suitable, i.e., that a geomagnetic storm is not in progress and energetic particles are available to provide amplification, the hydromagnetic waves may stimulate a Pc 1 pulsation event on the field line or on an adjacent field line. The proposed generation mechanism is basically a modification of the mechanism proposed by Bell (1976) for ULF wave generation by VLF transmitters.

Simultaneous ULF and VLF recordings made at Roberval show that many Pc 1 pulsation events have start times in or close to intervals of repetitive VLF activity, thus giving support to the above hypothesis. An illustrative example is shown in Figure 6. The data in this figure were obtained at Roberval during the approximate interval 0830 to 1100 UT on April 4, 1975. The well-defined Pc 1 pulsation event shown

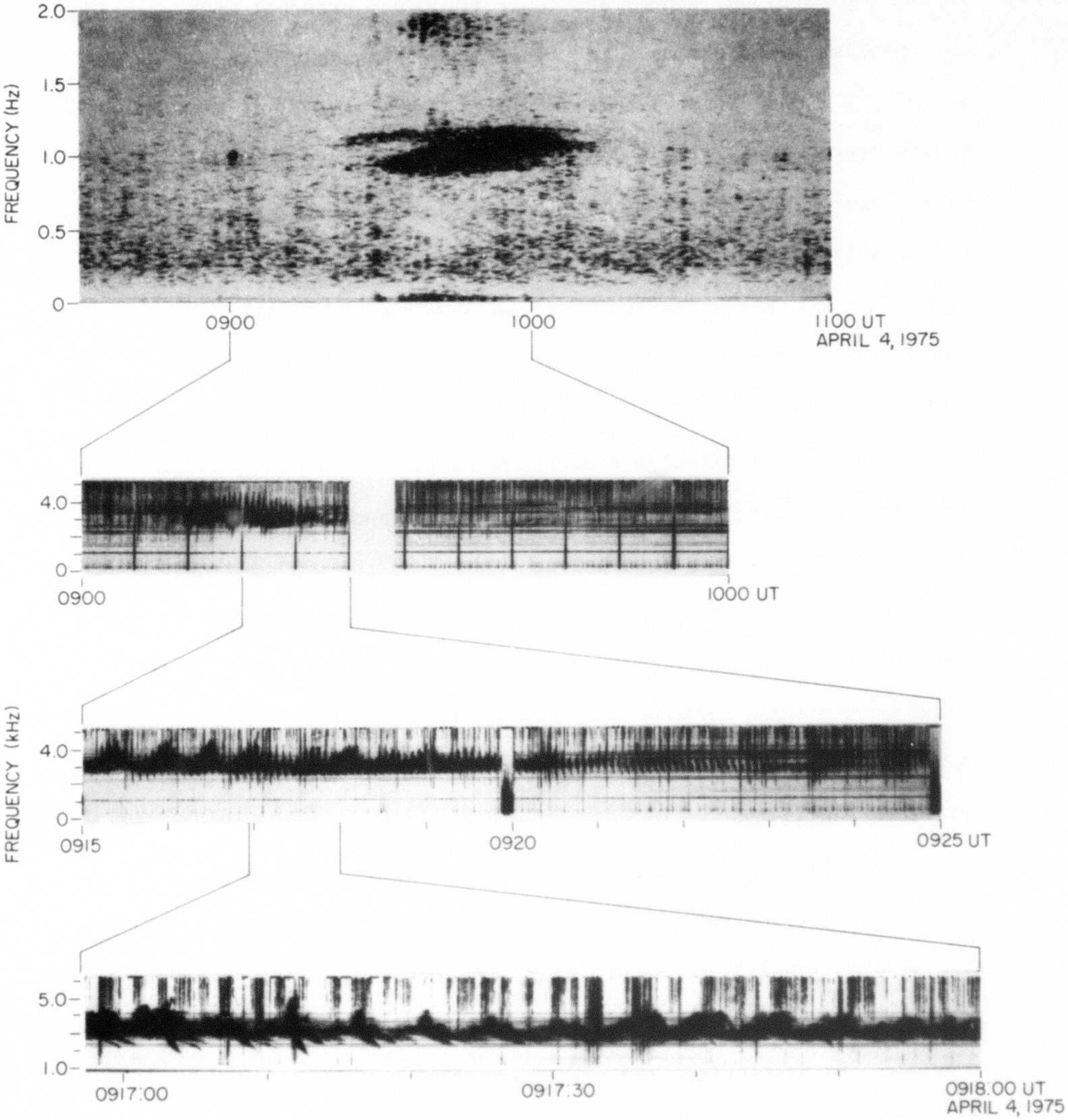

Figure 6. Spectrograms of North-South ULF and VLF data recorded at Roberval during the interval 0830 through 1100 UT on April 4, 1975. The top panel shows a Pc 1 pulsation event starting at (0919.8 ± 0.5) UT, and the three lower panels show the simultaneous VLF activity around this time.

in the top panel has higher and lower frequency branches both starting at approximately the same time. The higher frequency branch starts at (0919.8 ± 0.5) UT at a frequency of 1.07 Hz; the lower frequency branch starts at (0923.4 ± 0.5) UT at a frequency of 0.92 Hz. The three lower panels show spectrograms of (1) the repetitive VLF activity that started at approximately 0910 UT and ended at approximately 0925 UT, i.e., which started about ten minutes before the first appearance of the Pc 1 pulsation event and which continued until after both branches of the Pc 1 pulsation event had started (second panel), and (2) progressive expansions in time of the repetitive VLF activity shown in the second panel (third and bottom panels). This example is particularly interesting because of the well-defined occurrence of ULF and VLF activity. The Pc 1 pulsation event is preceded and followed by at least an hour with no detectable Pc 1 pulsation activity. Similarly the burst of repetitive VLF activity is preceded and followed by comparatively lengthy intervals with little VLF activity.

In addition to the large-scale correspondence between the occurrence of a burst of repetitive VLF activity and the subsequent appearance of a Pc 1 pulsation event, there are other detailed correspondences between the VLF and ULF activity which imply a possible cause and effect relation. In particular, two strong whistler trains are visible in the bottom panel of the figure in the interval 0917:00 to 0917:30 UT. The first of these whistler trains is initiated at 0916:58 UT (causative sferic) and five echoes can be detected. The repetition period at 3 kHz is 4.8 sec., giving an echo repetition frequency of

0.214 Hz. The fifth harmonic of this frequency is 1.07 Hz. The echo repetition frequency depends on the VLF frequency and is variable. However, the whistler energy in these above examples is more consistently present at 3 kHz than at other frequencies. It would therefore be expected that the repetition frequency (or one of its harmonics) at 3 kHz would be the most probable ULF stimulation frequency. As we have already observed, the Pc 1 pulsation event makes its first appearance at a frequency of 1.07 Hz.

The excellent correspondence between the occurrence of the two strong VLF whistler trains and the start of the Pc 1 pulsation event is strongly suggestive of a cause and effect relation, particularly when the correspondence in frequencies is considered. However, it should also be noted that the VLF activity, of which the two VLF whistler events are just a part, is also clearly repetitive. Not surprisingly, measurements indicate that this other activity also has a repetition frequency in the approximate frequency range 0.20-0.21 Hz. Thus, the repetitive VLF bursts could also be responsible for the stimulation of the Pc 1 pulsation event, and it is impossible in this one example to separate the general VLF activity from the VLF whistlers as the possible stimulating agent. Nevertheless, the example still provides strong evidence for the stimulation of Pc 1 geomagnetic pulsations by natural VLF activity.

There are several reasons why natural VLF emissions or whistlers may be superior to artificial VLF transmissions for the generation of Pc 1 pulsations. The most obvious reason is greater strength in the magnetosphere. In addition, present VLF transmitters are not good radiators at frequencies below about 5 kHz, yet these low frequencies may be best for precipitating energetic electrons into the lower ionosphere and starting the generation process. As illustrated by Figure 6, the maximum VLF whistler intensity often occurs at frequencies below 5 kHz (for the whistlers in Figure 6 the maximum intensity occurs in the range 2-3 kHz). Finally, for field lines near L = 4, the VLF emission or whistler echoing period is near 5 seconds and is therefore ideal for avoiding self-suppression of any wave-particle interactions that occur. The fifth harmonic of this period is centered in the Pc 1 pulsation frequency range. We have previously noted (Section 2.3, Chapter VI) the desirability of using a low VLF pulse repetition frequency (0.2 Hz) to avoid echo suppression of man-made VLF pulses.

5. Summary of Experimental Results

The experiments reported here show that VLF transmissions can modify the occurrence of Pc 1 pulsation events at the location conjugate to the VLF transmitter and also, by implication, at the transmitter location itself. The modification, which is not strong with present transmitter programs, appears to be effective for up to 24 hours, provided the transmissions are made at the right time of day. For transmissions from Siple Station, Antarctica, the modification occurred if the transmissions were made during the time of day when naturally-occurring Pc 1 pulsations occur most frequently; transmissions later in the day were ineffective.

There was some evidence that 1:1 stimulation of Pc 1 events occurred, i.e., that particular intervals of VLF transmissions stimulated particular Pc 1 pulsation events. However, differences between the characteristics of the ULF and VLF signals prevented the establishment of a definite relationship. Similar difficulties were experienced by Willis and Davis (1976) and, more recently, by Koons (1977). Further progress will probably require additional controlled VLF transmission experiments. Since these experiments require considerable transmission time and are expensive, it is suggested that transmission experiments be combined with an examination of naturally-occurring VLF and ULF signals. As we have noted, there is evidence that naturally-occurring repetitive VLF signals may stimulate Pc 1 pulsation events, and further studies of this natural stimulation process would undoubtedly provide new information about the most effective VLF transmission programs for ULF stimulation.

VII. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

We have obtained much experimental evidence indicating that ULF geomagnetic pulsations can be excited by controlled VLF transmissions into the magnetosphere from a ground-based transmitter. In addition, our measurements provide evidence that ULF pulsations can be stimulated by naturally-occurring VLF activity. However, as we noted in Section 2, Chapter VI, our experimental program using the Siple VLF transmitter ended in 1975 and could not be resumed before the end of the subject contract. Partly for this reason, we are unable to reach a firm conclusion regarding the conditions under which ULF hydromagnetic waves can be excited in the magnetosphere. It is reasonably clear that one important condition for Pc 1 pulsation generation is a low VLF pulse (or modulation) rate, i.e., a pulse rate at the lowest limit of the Pc 1 frequency range (e.g., 0.2 Hz). This condition has two advantages: (1) it allows for Pc 1 pulsation excitation at harmonics of the fundamental pulse frequency, and (2) it helps to avoid self-suppression in the wave generation process. Other desirable conditions for ULF wave excitation are described in Chapter VI. However, even when all the known desirable conditions for ULF excitation apply, it does not yet appear possible to excite a ULF pulsation event on demand. Thus, further active experiments with VLF transmitters will probably be required if further progress is to be made with the VLF method of ULF wave excitation. Because the results of our experiments and theory appeared to be consistent with the Bell (1976) mechanism for ULF excitation, we expect that this mechanism will continue to provide guidance for future experiments.

Our theoretical work on the cyclotron resonance wave-particle interaction (which appears to be basic to the ULF excitation mechanism) and on ULF wave propagation leads to two additional general conclusions. First, our progress with computer simulation indicates that it is a powerful and practical tool for the solution of magnetospheric wave-particle interaction problems in general and of the cyclotron resonance interaction for ULF excitation by VLF waves in particular. Extensions of earlier computer simulations have reproduced certain important results of linear theory, thus increasing our confidence in the approach. In addition, a method has been developed for calculating the flux of energetic electrons precipitated by a given VLF wave form in the magnetosphere. It was found, for example, that a typical VLF wave, of 10 mγ amplitude, can dump 2000 electrons/cm^{2}s (electron energies above 40 keV) into the lower ionosphere. This flux is sufficient to account for a number of observed perturbations of the ionosphere, and it supports one of the critical assumptions of the Bell mechanism. We conclude that a combination of VLF transmission experiments, guided by the Bell mechanism, and theory, based on the computer simulation approach, has the best potential for determining all the conditions for ULF stimulation by VLF waves in the magnetosphere.

The second conclusion derived from our theoretical work is that helium ions, and possibly other heavy ions (e.g., oxygen ions), may have a much stronger effect on ULF wave propagation in the magnetosphere than has been previously recognized. In fact, application of ray theory to the propagation of ULF waves in a multiple-ion medium shows quite different results from those obtained with the classical (and widely used) proton model. Our work using a particular interaction model suggests that strong interaction between ULF waves and protons may be limited by the presence of helium ions to a narrow band of frequencies. This conclusion is tentative, because it is based on the use of ray theory in regions where the wavelengths may be comparable on occasion to the scale lengths of the inhomogeneities, but it clearly has important implications in experiments to stimulate ULF geomagnetic pulsations. It appears therefore that better models of the magnetospheric medium need to be employed in studies of ULF wave propagation in the magnetosphere, and that the results of these studies need to be known if the results of experiments to stimulate ULF waves in the magnetosphere are to be properly understood.

Finally, we note that the VLF method of ULF wave generation has an important advantage over other possible methods: by using existing VLF transmitters, most of the cost of constructing a ULF wave generator can be avoided. In addition, if use can be made of the natural amplification properties of the magnetosphere at VLF and ULF, it is possible that large-amplitude ULF signals can be produced over large areas of the earth by using a VLF transmitter of only moderate power. Thus, given the advantages of low cost and an ability, already demonstrated, to stimulate and/or control Pc 1 geomagnetic pulsations, further exploratory research on the VLF method for the controlled artificial generation of ULF waves in the magnetosphere and ionosphere appears to be justified.

2. Recommendations

The following are our recommendations for further work:

(1) The theory of the Bell (1976) mechanism for ULF wave generation in the ionosphere and magnetosphere requires further study. In particular, the nature of its transient response needs to be investigated. As we have pointed out in this report, there is an apparent association between ULF geomagnetic pulsations of class Pc 1 and relatively short VLF wave trains, both man-made and natural, and knowledge of the transient response of the Bell mechanism would help in the interpretation of these observations.

(2) Further use of high-powered ground-based VLF transmitters to stimulate ULF geomagnetic pulsations should be explored. In particular, repetition of the Willis and Davis (1976) experiments is desirable, preferably in conjunction with some of the ionospheric diagnostics noted in recommendation (3) below.

Other means of launching ULF waves should also be considered. For example, the San Francisco Bay Area Rapid Transit (BART) System might also be usable as a source of ULF geomagnetic pulsations of class Pc 1, particularly if the system could be modulated during "off" hours to increase the intensity of frequency components in the Pc 1 range (i.e., 0.2-5 Hz).

(3) Further attempts should be made to stimulate ULF waves in the magnetosphere by means of modulated electron precipitation induced by VLF signals from Siple Station, Antarctica. It is particularly desirable that these attempts be accompanied by measurements of the VLF wave-induced electron precipitation in the ionosphere. For

example, Bremsstrahlung X-rays, auroral light (i.e., photometers), ionospheric absorption (i.e., riometers), and sub-ionospheric VLF propagation perturbations can all be used to detect precipitation-induced perturbations in the D and E regions of the ionosphere.

(4) The possibility that Pc 1 geomagnetic pulsations can be stimulated by natural periodic or quasi-periodic VLF activity, including VLF whistler trains, requires further study. The naturally-occurring VLF waves can have large amplitudes in the magnetosphere, and studies of the relationship between the natural VLF and ULF signals can provide information relevant to research on the artificial stimulation of ULF waves in the magnetosphere by VLF transmissions from ground-based transmitters.

(5) The theoretical work on VLF wave generation described in this report should be extended to include the full effects of magnetospheric inhomogeneity. At the same time, the analogous ULF wave generation case should be treated by using the same general theoretical approach, starting with the case of a homogeneous magnetosphere. Although a full-wave treatment of ULF wave propagation may be required in some regions, the ray theory should be used as much as possible because of its relative simplicity.

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