JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 85, NO. A7, PAGES 3360-3366, JULY 1, 1980

POWER THRESHOLD FOR GROWTH OF COHERENT VLF SIGNALS IN THE MAGNETOSPHERE

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Abstract. It is well known that coherent VLF signals injected into the magnetosphere from Siple Station, Antarctica, often show temporal growth of 20-30 dB and emission triggering, as observed at the conjugate point, near Roberval, Quebec. In a new kind of experiment it has been found that when the input power to the transmitting antenna is reduced below a 'threshold' value P_t, growth and triggering cease. Below P_t the output is proportional to the input. In one typical experiment the peak received power increased by 24 dB when the input power to the antenna crossed the threshold value of 1000 W (estimated radiated power of 10 W). The value of P_t varied widely depending on the duct involved and on the time, changing as much as 10 dB in less than 1 hour. As the power was lowered during multipath propagation, the last duct to be cut off was found to terminate nearly overhead at Siple, as was expected, assuming all ducts to be equally active. Minimum radiated power for growth and triggering was 1 W. One possible explanation for the threshold effect is background noise (e.g., plasmaspheric hiss) that prevents the instability from getting started. Another is a drop in temporal growth rate to below zero at low signal level. Measurement of P_t might possibly serve as a ground-based diagnostic for magnetospheric flux levels, assuming calibration by satellite particle detectors.

Introduction

Since the beginning of active VLF experiments at Siple Station, Antarctica, in 1973, much has been learned about the response of the magnetosphere to the injection of coherent waves near L = 4 [e.g., Helliwell and Katsufrakis, 1978]. Exponential growth rates of 30-200 dB/s and total growths of the order of 30 dB are often observed on ducted signals prior to amplitude saturation. Following saturation, emissions of rising frequency are frequently triggered, with bandwidth usually less than 1% of the carrier frequency. Temporal growth and the associated triggered emissions will be referred to collectively as the coherent wave instability.

In addition to growth and triggering, wave-wave interactions, including entrainment and suppression effects, are also frequently observed. Especially interesting is the observation that strong coherent emissions can be triggered by Siple signals during periods when there are no other detectable magnetospheric signals in the ground-based recordings. This circumstance demonstrates the existence of a triggering threshold for the coherent wave instability.

In the present paper we describe an experiment to measure the coherent wave input-output characteristic of the magnetosphere as a function of input power level. It is found that the output is proportional to the input until a critical or threshold power P_t is reached, above which temporal growth of 20-30 dB and triggered emissions occur. As power is increased above P_t, the output appears to approach a saturation level. The value of P_t varies widely with time and is different for different ducts.

Description of Experiment

Coherent VLF signals are injected into the magnetosphere from Siple Station, Antarctica, and are received at the conjugate point, Roberval, Quebec. The transmitter is a solid-state switching device, tunable over the operating bandwidth at intervals of 10 ms [Helliwell and Katsufrakis, 1974, 1978]. The transmissions reported here occupied a 1-kHz band, usually centered in the 2.5- to 5.0-kHz range.

Signals from the Siple transmitter usually travel to Roberval over several magnetospheric field-aligned paths. In terms of ionospheric endpoint position the paths of whistlers excited by natural lightning may be distributed over distances up to 1000-2000 km from the receiving station. In contrast, paths excited by the Siple transmitter and received at Roberval, and in an echoing mode at Siple, are found to lie with ~200 km of the stations [Carpenter and Miller, 1976; Leavitt et al., 1978]. Information on the propagation of Siple transmitter signals is obtained by comparing their arrival time characteristics with those of natural whistler mode signals [Carpenter and Miller, 1976]. In some cases the spectrogram of the received signal suggests propagation on a single discrete path, and in such cases a corresponding whistler component, often of exceptional intensity or echoing properties, can usually be identified [Carpenter and Miller, 1976]. In many other cases there is clear evidence of propagation on a number of discrete paths. Figure 1 shows a simplified diagram of such multipath activity and its interpretation.

Figure 1a shows frequency-time diagrams of rising frequency ramps. The first ramp is shown as transmitted at Siple; the following three represent the spectrum as received about 2 s later at the conjugate station. (The frequency range of the ramp is exaggerated, and the small curvature due to dispersion is omitted.) The travel times of the three discrete ramps at frequency f_o are compared to the travel times of multicomponent whistlers recorded during or near the period of Siple transmissions. Ideally, a one-to-one relation between the ramps and discrete whistler components would be found, as indicated by the vertical dashed lines connecting Figures 1a and 1b. From dispersion analysis of the whistlers the magnetic shell parameter or equatorial radius of the paths of propagation

Paper number 80A0333.
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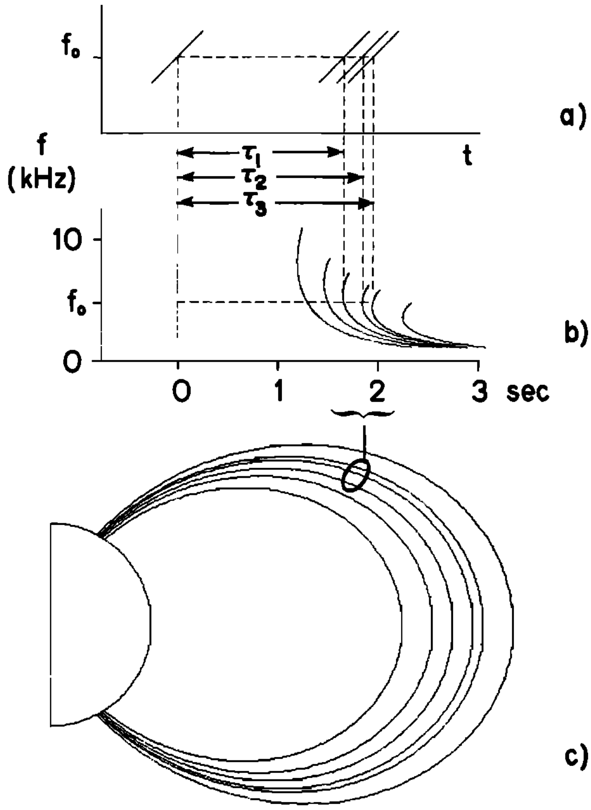

Fig. 1. Diagram illustrating the use of whistlers to locate the propagation paths of Siple transmitter signals. (a) Siple frequency ramp as transmitted ($f = f_0$ at $t = 0$) and as received at Roberval after propagation on three of six whistler paths. (b) Corresponding multipath whistler. (c) The six whistler paths, with the three Siple signal paths circled.

may be determined, as indicated schematically in Figure 1c.

In practice, fine structure in Siple travel times may be difficult to resolve (Figure 2a, for example). Furthermore, whistlers may exhibit more fine structure than do the Siple signals because of their propagation paths terminating both within and beyond the region of observed Siple signal propagation. In such cases it is usually possible to relate the range of Siple travel times (τ_1 to τ_3 in Figure 1a) to a corresponding range of components within the whistler. This point is discussed later.

In the experiments described below, transmitter power was changed at intervals of 50 s by manual operation of an autotransformer. The experiments were conducted when the Siple operator determined that conditions for one-hop propagation to Roberval were favorable. He observed two-hop behavior at Siple and received reports of one-hop signals from the Roberval operator via the ATS 3 satellite.

In this paper the input power to the magnetosphere is given in terms of power P_a delivered to the antenna at the upper frequency limit of the transmitted signals. The actual radiated power varies with frequency and is about 1% of P_a at 4 kHz. Total variations in radiated power over the transmitter bandwidths are estimated to be a few decibels, or less than the power step size that was usually employed.

Data for this study were obtained on April 18, May 20, and June 15, 1977. The durations of the power step transmissions were 30 min, 45 min, and approximately 3 hours on those days, respectively.

Experimental Results

The 'threshold' effect is illustrated in Figure 2 by a series of frequency-time records that are ordered from top to bottom in time and in 4-dB steps of transmitter power. Frequency from 2.5 to 5.0 kHz is displayed versus time in seconds. The modulation format consisted of a series of 1-s fixed-frequency pulses and rising and falling frequency ramps, as shown in the bottom panel of Figure 2. Recorded segments are shown at intervals of 50 s; each case was followed by a 20-s keyup during which the power step adjustments were made. The P_a levels with respect to 24 kW (in 4-dB steps) are indicated at the left.

At the three highest power levels the records show clear evidence of wave growth and triggering of emissions on multiple paths. In Figure 2b, for example, at least three distinct paths are detectable in both the rising and the falling ramps. The spread in travel times of the ramps at a given frequency is about 500 ms, a typical value. Between the −8- and −12-dB steps there was a significant decrease in received signal intensity, emission triggering, and multipath activity. At the −16-dB step the signal was weak and was seen on only one path. There was also no frequency broadening or triggering and no clear evidence of temporal growth. At the −20-dB level the signal had disappeared in the background noise.

The transmitter power at which temporal growth first appears will be called the threshold power, denoted by P_t. In these experiments, P_t is taken to be the average of the transmitter powers (in log units) just below and just above the threshold. Thus in Figure 2 the strongest path had a P_t of 14 dB below 24 kW, or 960 W (nominal radiated power ~10 W).

A quantitative measurement of the threshold effect is shown in Figure 3 for two power step sequences taken just before and after that of Figure 2. Peak amplitude at a single frequency (3.51 kHz), averaged over all the pulses at that frequency at a given power level, is plotted versus antenna input power P_a on a log scale. Pulses 1 and 6 correspond to the highest P_a levels, and 5 and 10 to the lowest P_a for which there was a detected signal (they correspond to Figure 2e). Across the threshold the received power increased by about 24 dB in each case. The threshold powers are estimated to have been 10 and 14 dB above 100-W input, respectively. For both cases the output signal appeared to approach a saturation level as input power was increased above the threshold value. At input powers below the threshold value there was no obvious temporal growth, as shown by Figure 2e, and the output was proportional to the input (see points 9 and 10 of Figure 3).

The results are complicated (and illuminated) by temporal variations and multipath effects.

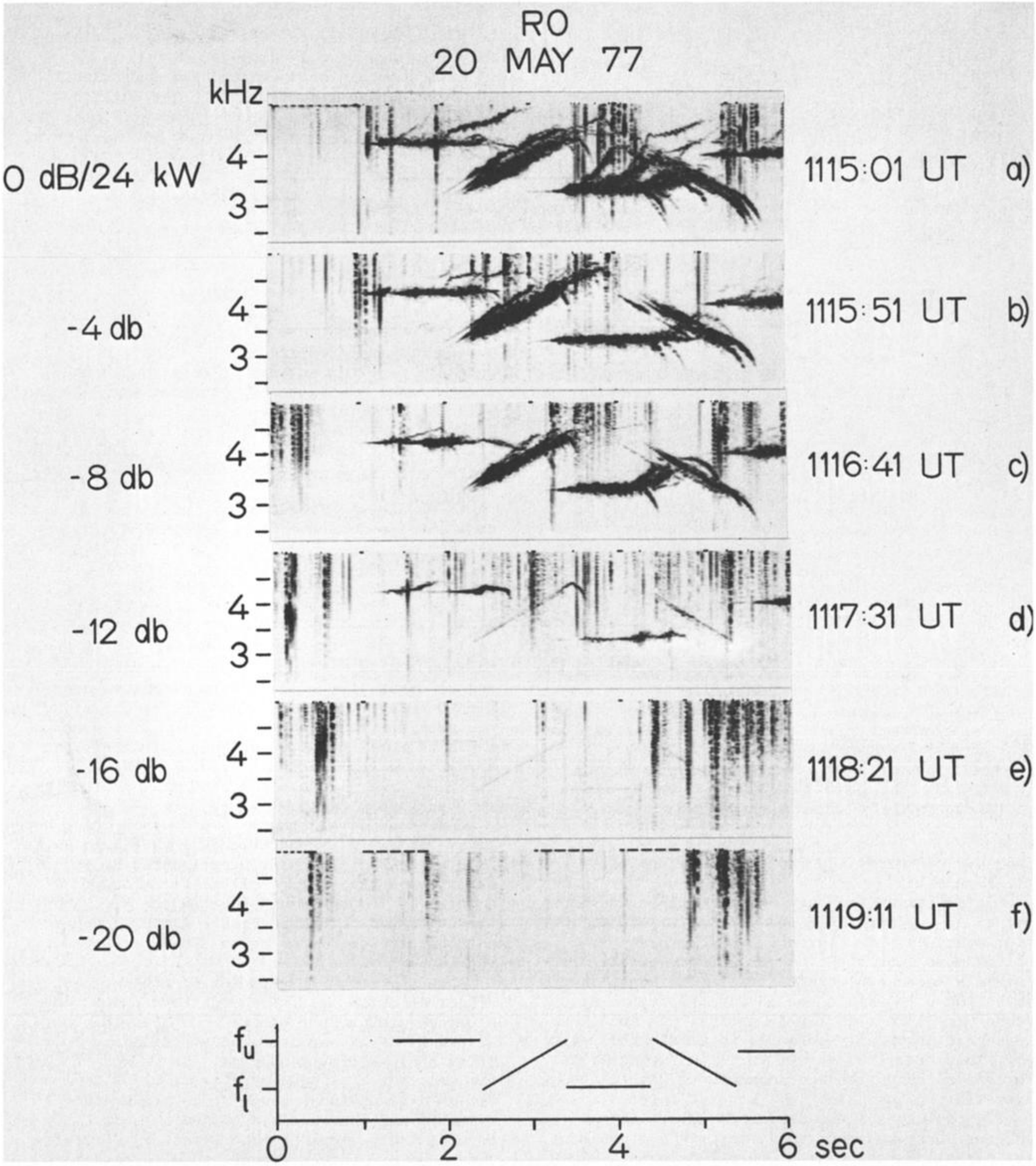

Fig. 2. Frequency-time records of magnetospheric response as a function of input power to the antenna in steps of 4 dB. The program as transmitted from Siple to Roberval on May 20, 1977, is shown in the bottom panel. The threshold power condition occurred between panels d and e. At ~-20 dB the intensity of the received signals, shown in panel f, dropped below the system noise.

The presence of multipath activity was indicated both through dispersion measurements and direction finding. Figure 4 shows a spectrogram of a one-hop whistler received at Siple during the power step experiments of May 20, 1977. Above the whistler are marked the travel times at 4.23 kHz for four multipath frequency ramps, measured at ~1115 UT. A number of closely spaced whistler components fell within the overall travel time range of 1.98-2.38 s, but because of the large number of closely spaced traces in the whistler record a one-to-one re-

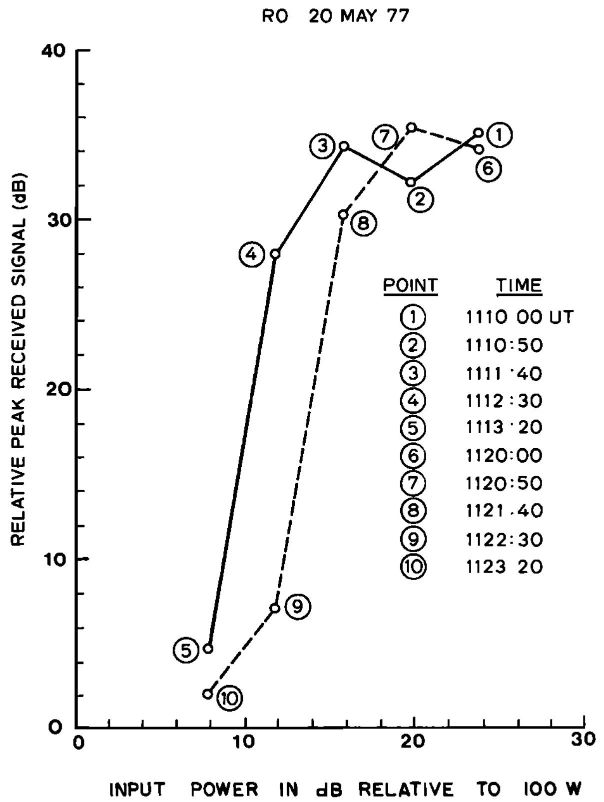

Fig. 3. Variation in received signal power as a function of input power in two power step sequences transmitted from Siple on May 20, 1977. The sequences are numbered 1-5 and 6-10. The time at which each measurement was made is listed in the figure. The output power increased 24 dB when the threshold power was crossed. For run 1-5 the threshold occurred at 10 dB, and for run 6-10 it occurred at 14 dB.

lation between Siple signal paths and whistler components could not be established. A corresponding range of whistler components could be identified, however, and thus a range of field-aligned paths could be determined according to the scheme of Figure 1. This range corresponds to a belt passing over Roberval and extending less than 100 km north and south of the station.

A VLF direction finder [Leavitt et al., 1978] at Roberval was able to resolve two or three different arrival bearings during a number of the 30-s transmission segments [Carpenter, 1980]. As the power was reduced, the bearing fluctuations decreased markedly, in a manner consistent with previous studies of the transition from multipath to single-path conditions [Leavitt et al., 1978].

Because of multipath effects the time to saturation on any given path could not be accurately measured. However, the overall time to saturation showed a tendency to decrease as input power increased, as was expected. The growth rate was estimated to be ~40 dB/s, an unusually low value. For a 12-dB decrease in input power the increase in time to the saturation level, assuming a constant growth rate of 40 dB/s, would be 0.3 s, a value that was consistent with the data.

Temporal Variations

Within the 3 days of data surveyed, the threshold power P_t was found to vary from about 200 W to above 10 kW, a range greater than 17 dB. P_t was found to vary not only from day to day but also relatively widely within a period of several hours. On April 18 and May 20, when the current Kp values were 3 and 2- respectively, P_t was near 10 kW. On June 15, when the index was much lower (0+), P_t was near 1 kW over much of the observation period. Temporal variations in P_t on June 15 are illustrated in Figure 5, covering an observing period of approximately 3 hours. Two types of symbols are used. Circles represent the lowest input power step above an observed threshold, while circles with arrows indicate the lowest power step when all power steps were above P_t. The figure shows a prolonged period in which P_t was below 1 kW, with some temporal variation. Following 1730 UT there was a rapid rise in P_t to near 8 kW, followed by a brief recovery to lower values at the end of the observation period.

The apparent sensitivity of the threshold effect to particle activity in the magnetosphere is illustrated by a series of six transmissions, spaced 50 s apart, shown in Figure 6. During this period, lasting slightly over 4 min, the natural activity — especially multicomponent whistlers — increased in terms of the number of events, average intensity levels, echoing of discrete elements, etc. During the same period the Siple signals showed a corresponding increase in strength, bandwidth, and triggering of emissions, in spite of the progressive lowering of P_a from 700 to 200 W.

Discussion

This experiment revealed an abrupt transition, or threshold, between the conditions of zero and high (20-30 dB) temporal growth as transmitter power was raised. The transmitter power at this threshold, called P_t, varied widely with time and was path specific. That is, each ducted path exhibited a particular P_t at a given time.

Since no general theory of the coherent wave instability is yet available, we cannot give a firm explanation of the threshold effect. Previous experiments [Helliwell and Katsufrakis, 1974; Stiles and Helliwell, 1977] have shown that the measured temporal growth is usually exponential at levels substantially below saturation. A computer simulation of a feedback model in a spatially limited homogeneous medium also shows exponential growth at all levels below saturation [Helliwell and Crystal, 1973]. Thus there is yet no evidence in the observed and simulated growth behavior of a reduction in growth rate at small signal levels.

One possible explanation for the threshold effect is that coherence of the signal is reduced by the presence of background noise. It is well known that temporal growth of a coherent signal can be reduced when a noisy interfering signal is added to the coherent input signal [Raghuram et al., 1977]. However, evidence of the required background noise level has not been found. For example, in Figure 2a the subthreshold signal from Siple was easily detected, and

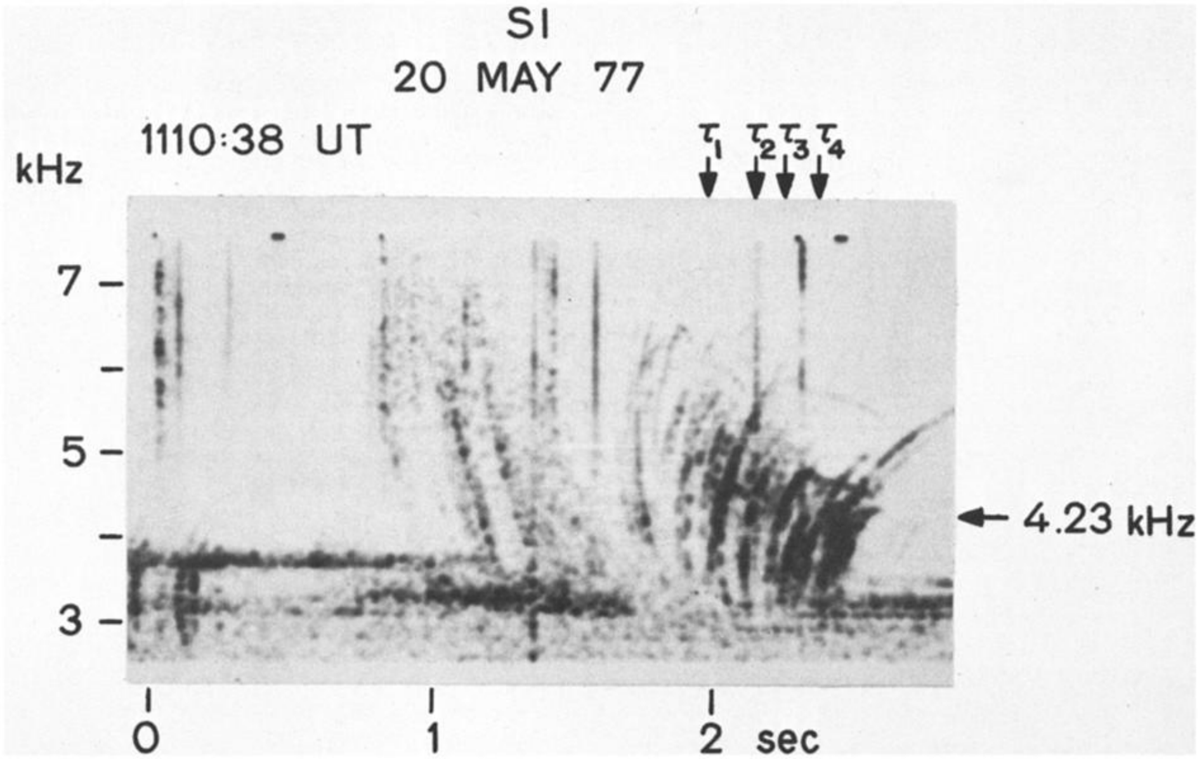

Fig. 4. Frequency-time record of a one-hop multicomponent whistler recorded at Siple Station close to the time of the power step experiment shown in Figure 2. Associated Siple signal travel times at 4.23 kHz, determined near 1110 UT from frequency ramps (see Figure 1a), are marked above the record. The whistler exhibits multiple traces, one or more of which corresponds closely to each Siple travel time.

yet there is no obvious evidence of magnetospheric noise on the spectrogram. However, it is conceivable that the interfering noise was of a type (e.g., plasmaspheric hiss) that cannot reach the ground because of high wave normal angles [Muzzio and Angerami, 1972]. Another possibility is that the inhomogeneity of the medium introduced unfavorable phase shifts in the phase-bunched currents at low signal levels such as to reduce the net stimulated radiation. This question will be addressed in a later paper.

Our results provide a simple explanation for the horizontal range in distance D from the Siple transmitter within which growth and triggering along associated field lines have been observed. This range, previously deduced from dispersion and direction-finding techniques, is reported to be about 200 km [Carpenter and Miller, 1976; Leavitt et al., 1978]. We propose that D is ~D_t, a spatial equivalent of P_t. That is, P_t refers to excitation at reduced power (~-14 dB below peak) of a nearby or essentially overhead duct, while D_t is the distance at which upgoing wave fields are ~14 dB below the fields produced overhead during normal peak power operation. That D_t indeed corresponds to a ~200-km distance is indicated by the work of Scarabucci [1969], who reported on the field strength of upgoing 12.5-kHz Omega signals from the Forest Port, New York, transmitter, as observed on the OGO 4 satellite. He found good agreement between the data and full wave calculations which predicted a falloff of about 12 dB within 200 km of the transmitter. For the Siple transmitter there are differences in frequency, antenna pattern, and ionospheric properties, but a range of ~200 km would also be expected.

To complete the argument on D_t, we need to establish that the typical P_t level of ~-14 dB was observed on an essentially overhead duct. This was done for the case of Figure 2, considered typical, from a combination of arrival bearing and dispersion information. Carpenter [1980] has estimated the corresponding duct endpoint to have been ~50-70 km northwest of Rober-

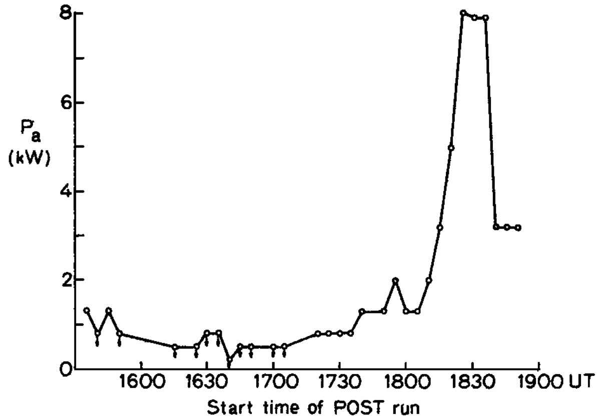

Fig. 5. Variation of power threshold in kilowatts as a function of time for measurements made at Roberval on June 15, 1977. Circles give measured threshold power, while circles with downward directed arrows indicate that the threshold power was below the value plotted.

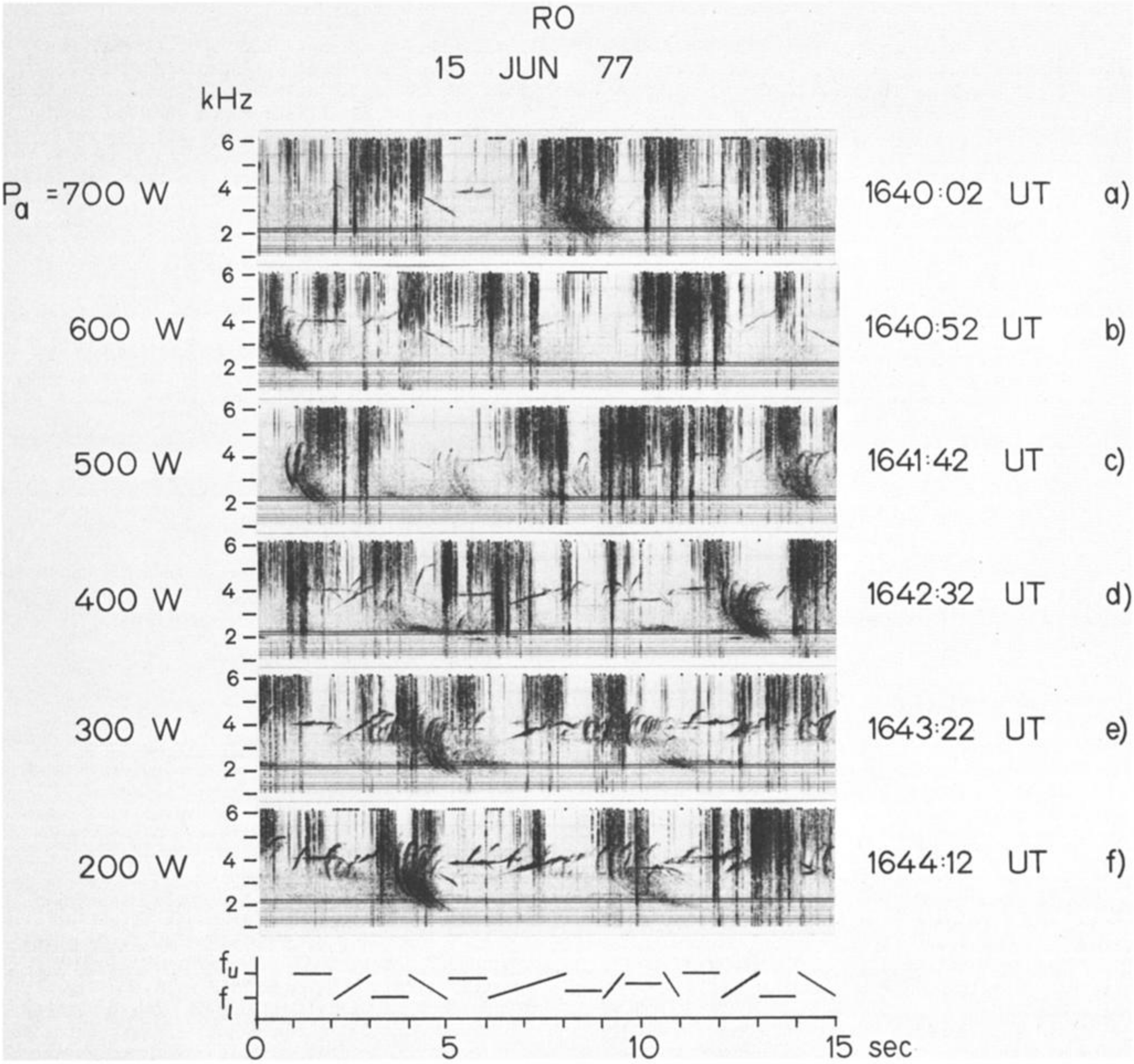

Fig. 6. Variation of Siple signal growth and emission activity with time during a 4-min period on June 15, 1977 (see Figure 5). The transmitter format is shown in the lower panel. Activity from both Siple pulses and natural whistlers increased with time, while the input power to the antenna decreased with time (see left), suggesting that the particle fluxes must have been increasing. The activity in panel f was excited by Siple pulses having an estimated radiated power of 2 W.

val. Seely's [1977] tracings of field lines between Siple and Roberval in a hybrid international geomagnetic reference field/Olsen-Pfitzer magnetic field model place the conjugate to Siple slightly north and west of Roberval and ~40 km distant. Hence we assume that the corresponding duct was nearly overhead at Siple.

Using the threshold effect, we can explain a number of previously puzzling features of magnetospheric wave emissions. In the Kennel and Petschek [1966] theory, growth rate is independent of signal level for small signals. This means that any input signal, no matter how weak, should grow until it reaches saturation, assuming that appropriate particle fluxes are present. Consequently, we would expect magnetospheric wave activity to reflect mainly the particle distribution function. However, as we have shown here, coherent signals do not follow this prediction. Thus the magnetosphere may be entirely quiescent for $P < P_t$. However, when $P > P_t$, large growth (20-30 dB) occurs, and emissions are triggered. Except for suppression effects, which can be avoided by appropriately changing the signal frequency with time, triggering can be repeated more or less indefinitely until the particle population is significantly depleted. Thus magnetospheric wave activity depends to a considerable extent on the level of coherent wave input from the ground.

A possible correlation (as yet unproved) between chorus occurrence for L > 4 and areas of electrical power generation [Luette et al., 1977] might be explained in terms of the power threshold effect. Over industrial areas the harmonic radiation from power lines is increased, causing more emissions to be triggered. The resulting waves precipitate electrons, thus acting to limit the total flux. When the particle flux increases faster than it can be removed by wave-induced scattering, the threshold for temporal growth is reduced, eventually becoming so low that any noise disturbance can trigger growth. In this event the resulting emissions would appear to arise spontaneously and might be expected to fill frequency-time space, giving a spectrum more like hiss than discrete emissions. Moderate or weak intensity waves injected from the ground would then have little effect on emissions.

Thus we are led to expect that the influence of signals from the ground on the magnetospheric noise level will vary with the particle flux levels. At low fluxes, only the stronger ground signals exceed the temporal growth threshold. At high fluxes, virtually any input signal will show growth and triggering, giving rise to many emissions that tend to suppress growth of an external signal. Thus there is a range of flux over which external coherent signals will exercise a controlling role in emission triggering. To test this hypothesis, we need to know how the ratio of triggered to spontaneous emissions varies with particle flux levels.

Controlled experiments on wave growth require transmitter powers well above P_t for an overhead duct, so that the area of growth excitation will be large enough to include one or more ducts during periods of appropriate particle activity. The new 'Jupiter' transmitter at Siple (dedicated in January 1979) normally operates at a power level roughly 7 dB greater than that employed in the presently reported experiments. We estimate that the area of the excitation region is correspondingly increased by a factor of about 2.

Because P_t appears to depend inversely on the flux of energetic particles, this quantity may be a useful measure of the fluxes of electrons that resonate with the wave, at least in the range below wave saturation. Together with path diagnostics, P_t could provide a relative measure of particle flux as a function of L value and electron energy, thus augmenting direct particle data obtained by satellite.

Other VLF stations (e.g., NAA) that are not accessible to controlled experiments of this kind could still be used to obtain flux information based on the threshold effect. The idea would be to measure the distance D_t beyond which the signals from a given transmitter are too weak to excite wave growth and emissions. A direction finder would locate the exit points of the whistler mode signals. The relation between D_t and particle flux could be obtained from satellite particle detectors passing through the flux tubes illuminated by the transmitter.

Acknowledgments. We thank field observers J. Doolittle and W. Armstrong (Siple Station) and R. Taillefer (Roberval Station) for conducting the experiments and J. P. Katsufrakis for his supervision of the Stanford field program. We thank J. Yarbrough for assistance in data reduction and Kristine Dean and Gabrielle Daniels for assistance in preparing the typescript. This research was supported by the Division of Polar Programs of the National Science Foundation under grants DPP74-04093, DPP76-82646, and DPP78-05746.

The editor thanks R. L. Dowden and D. Nunn for their assistance in evaluating this paper.

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(Received January 25, 1980; accepted February 22, 1980.)