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Brief Reports

A Case of Artificial Triggering of VLF Magnetospheric Noise during the Drift of a Whistler Duct across Magnetic Shells

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A case study is presented of the concurrent and apparently related behavior of four magnetospheric phenomena: (1) whistler 'ducts,' (2) cross-L drifts of tubes of ionization, (3) an abrupt upper intensity cutoff of ducted whistlers at $f_{H0}/2$, where f_{H0} is the minimum electron gyrofrequency along the path, and (4) artificial triggering of VLF whistler-mode noise at $f \sim f_{H0}/2$. The event occurred on June 17, 1965, near local midnight, and involved the inward drift of a whistler duct through $\sim 0.2\ L$ near $L = 3$. Triggering of magnetospheric noise by NAA transmissions at 17.8 kHz occurred when the minimum gyrofrequency on the drifting path became twice the NAA frequency.

INTRODUCTION

This note describes a case study of the concurrent and apparently related behavior of four magnetospheric phenomena:

(1) Whistler 'ducts,' discrete paths along which waves are guided between conjugate hemispheres [*Helliwell et al.*, 1956; *Allcock*, 1962; *Storey*, 1962; *Smith*, 1961]. The embodiment of these ducts is believed to be tubes of enhanced ionization [*Smith*, 1961]. Direct observation of ducts in space was recently achieved on OGO 1 and OGO 3 through detection of whistlers whose properties changed discretely as a series of ducts was encountered [*Smith and Angerami*, 1968; *Angerami*, 1969].

(2) Cross-L drifts of tubes of ionization. Recent whistler studies have indicated several types of cross-L drift motions within the plasmasphere near 4 R_E [*Carpenter*, 1966; *Carpenter and Stone*, 1967]. These motions include slow inward and outward drifts of the order of 0.1 R_E/hour (at the equator), lasting 1–10 hours, and fast inward drifts of the order of 0.3 R_E/hour lasting ~1–2 hours. The slow drifts are common during periods of reduced substorm activity; the fast inward motions appear to be concurrent with magnetospheric substorms occurring near the longitudes of the whistler observations [*Carpenter and Stone*, 1967].

(3) An abrupt upper intensity cutoff of ducted whistlers at $f_{H0}/2$, where f_{H0} is the minimum (approximately equatorial) gyrofrequency along the path [*Carpenter*, 1968]. This cutoff effect is believed to be related to the half-gyrofrequency ducting limit predicted by *Smith* [1961], who showed that a ray trapped in a duct will be untrapped beyond a point at which its frequency is half the local gyrofrequency. Evidence of the untrapping phenomenon has recently been found in OGO 3 data by *Angerami* [1969].

(4) Artificial triggering of VLF whistler-mode noise at $f \sim f_{H0}/2$. A recent ground-based whistler study [*Carpenter*, 1968] showed evidence that triggering of magnetospheric whistler-mode noise by signals from a low-power (~100 watts) VLF transmitter occurs preferentially on the magnetic shell for which f_{H0} is within a few per cent of twice the transmitter frequency. Triggering by high-power transmitters (~10^6 watts) has been observed for $0.4\ f_{H0} < f < 0.5\ f_{H0}$ [*Kimura*, 1967; 1968], but a 0.5-f_{H0} preference is evident, particularly during periods when the probability of triggering is low.

A possible dynamic test of all four phenomena would be to identify the magnetic shell on which triggering from a particular transmitter is most probable, and then to find a substorm drift event in which a whistler duct moves through this particular shell. An idealized experiment of this type is illustrated in Figure 1(*a*), which shows a tube drifting inward from time t_1 to time t_3 and passing through the 'triggering' region at time t_2. Throughout the observing period there is assumed to be steady source activity in one hemisphere, both from a VLF transmitter *T* operating at frequency f_T and from whistler-producing lightning flashes. Figure 1(*b*) shows a possible sequence of spectrums received in the conjugate area at *R* at times t_1, t_2, t_3. At time t_1, $f_T > f_{co} = f_{H0}/2$ (f_{co} is the upper cutoff frequency), and there is no propagation on the path from *T* to the conjugate region. Only the direct signal propagating under the ionosphere from *T* to *R* appears on the spectrum.

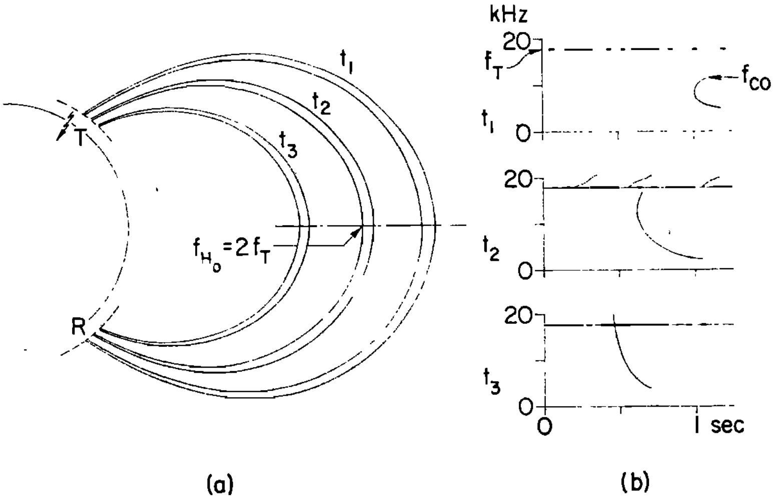
At time t_2, $f_T \sim f_{co} = f_{H0}/2$. Signals from *T* begin to propagate over the magnetospheric path to *R* and are indicated by the faint background line accompanying the code at f_T. Discrete triggered noises are observed at t_2, because the condition $f_T \sim f_{H0}/2$, shown by the statistics to be 'preferred' for triggering, is now fulfilled.

At time t_3, $f_T < f_{co} = f_{H0}/2$. Since $f_T < f_{co}$, whistler-mode signals from *T* continue to propagate over the path, but triggering of discrete noises is not detected, illustrating in time the statistical prediction of decreasing triggering probability with decreasing f_T/f_{H0} below 0.5.

A Case Study; General Features

Several events of the type just described have been identified; one illustrates particularly well the time interval corresponding to t_1 to t_2. This is a case observed at Eights, Antarctica ($L \sim 4$), during a period of NAA transmissions at 17.8 kHz from Cutler, Maine, in the conjugate region. The local time was ~00–03 on June 17, 1965, about 44 hours after the sudden commencement of a magnetic storm ($Dst \sim 100\ \gamma$, maximum $Kp = 7o$). Certain features of the event are plotted versus UT (bottom) and LT at Eights (top) in Figure 2. The upper part of the figure shows 30-MHz riometer information from Byrd Station (located at $L \sim 7$ and about 1 hour from Eights in magnetic local time). At the bottom of the figure are horizontal marks indicating that during successive observing periods (at 15-minute intervals), NAA transmissions were either Morse code at 17.80 kHz or FSK between 17.800 and 17.850 kHz.

The whistler measurements of radial drift for the June 17 event were made from a combination of 0.2–10 kHz continuous magnetic tape recordings and 0.2–30 kHz one-minute synoptic



(a) (b)

Fig. 1. Idealized dynamic test of the occurrence of triggered VLF noise on the particular magnetic shell for which transmitter frequency f_T is half the minimum path gyrofrequency $f_{H0}/2$. A whistler duct is imagined to drift across magnetic shells between times t_1 and t_3, crossing the $f_{H0}/2$ shell at time t_2. Associated VLF spectra received in the conjugate hemisphere are indicated at the right.

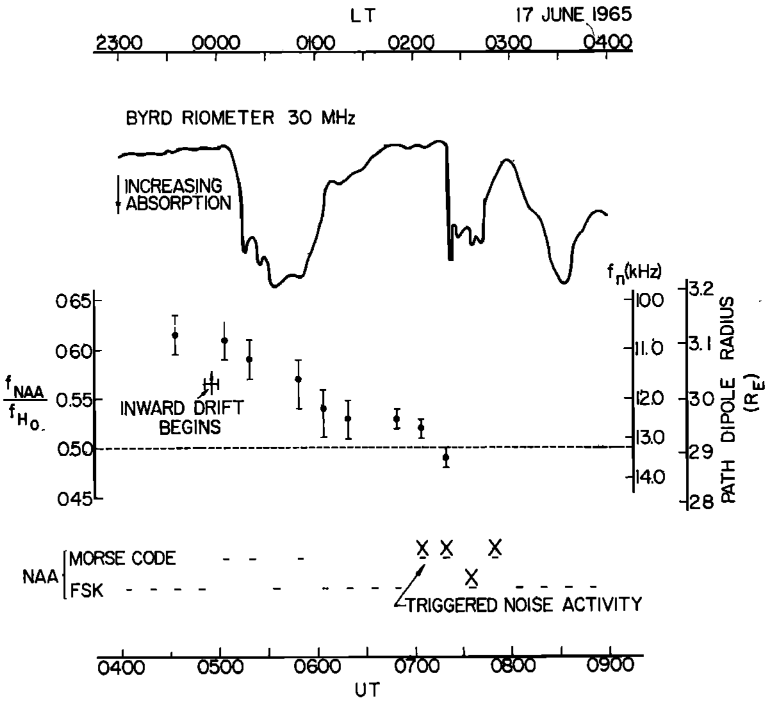


Fig. 2. Some details of a case corresponding to the t_1-to-t_2 interval in Figure 1. The path drift observations (middle) were made at Eights, Antarctica ($L \sim 4$); the substorm indication (top) is from a riometer at Byrd, Antarctica ($L \sim 7$). Rapid cross-L drift of a whistler path occurred during substorm activity on June 17, 1965. Observations of NAA transmissions of Morse code and FSK (50-Hz shift) at 17.8 kHz are indicated at the bottom. X's show the isolated interval during which magnetospheric noise was triggered by NAA. At this time whistler path nose frequency correspond to the 't_2' condition of Figure 1. (The drift measurements stop at 0720 due not to a cessation of whistlers but to insufficient definition of the whistler nose in later synoptic runs.) See text for further details.

recordings spaced at 15-minute intervals. The continuous records provided a means of verifying the persistence of a given path or duct, whereas the synoptic data provided details of whistler nose frequency f_n and upper cutoff frequency f_{co}. The quantities f_n and f_{co} were scaled from spectrograms, and f_{H_0} was calculated using the relation $f_n = 0.37\ f_{H_0}$ (from *Angerami* [1966]). Dipole coordinates were used to relate f_{H_0} and equatorial radius.

The drift event is summarized in Figure 2 by plotted values of the ratio $f_{NAA}/f_{H_0} = 17.8 \times 10^3/f_{H_0}$ (left) and of the corresponding whistler nose frequency and path dipole equatorial radius (right). A single 'cluster' of whistler paths was tracked from 0435 to 0720 UT. Beginning at ~05 UT the path was observed to drift inward in equatorial radius through $\Delta R \sim 0.2\ R_E$, from $R \sim 3.1\ R_E$ to $R \sim 2.9\ R_E$. Between ~05 and 07 UT, the deduced value of f_{NAA}/f_{H_0} for the path decreased from ~0.60 to ~0.50, and NAA-triggered emissions (denoted by X's) were observed as the 0.50 condition was reached. (The drift measurements stop at 0720 due not to a cessation of whistlers but to insufficient definition of the whistler nose in later synoptic runs.)

Details of the Path Drift Measurements

Figure 3 shows a sequence of events comparable to the pair of spectra representing t_1 and t_2 in Figure 1(*b*). Arrows and the origin of the time scale indicate the initiating impulses for the various events. In the top panel is a whistler recorded at 0505 UT (~00 LT), near the beginning of the observed inward drift. (There are 2 main whistler components, but only the first persisted throughout the drift interval.) At this time $f_n \sim 11$ kHz (path equatorial radius $\sim$3.1 R_E), $f_{co} \sim 15$ kHz, and the ratio f_{NAA}/f_{H_0} is $\sim$ 0.61 (cf. Figure 2). (The error flags on values of f_{NAA}/f_{H_0} in Figure 2 represent the uncertainty in measuring nose frequency f_n. In each case the nose frequency of the leading edge of the trace was scaled.)

Near 0510 UT, the onset of a substorm absorption event is indicated by the Byrd riometer trace in Figure 2. During the substorm event, the scaled value of f_n (and thus f_{H_0}) increased rapidly, so that by 0605 UT, the ratio f_{NAA}/f_{H_0} was $\sim$0.54. The average inward drift velocity deduced for the path is $\sim$ 0.15 R_E/hour (at the equator), which corresponds to a magnetospheric electric field with a westward component of $\sim$1 mv/m at 3 R_E. The inward drift actually began at 0457 ±3 min (arrow in Figure 2), some 13 min before the onset of the main substorm event. Such an effect has been noted in an earlier study of substorm associated drifts [*Carpenter and Stone*, 1967].

The form of the whistlers at 0605 UT is shown in the second panel of Figure 3. The nose frequency is now about 12.5 kHz, and the upper cutoff f_{co} appears to be within a range less than 1 kHz below the NAA-FSK signal. (This comment is based on visual examination of several events in the 0605 run.) The decrease in travel time associated with the reduced path length is clearly evident.

Between 0605 and 0705 UT there is a lull in substorm activity (cf. Figure 2), and the position of the whistler path changes only slightly. After 0700 further inward drift occurs, apparently associated with a new substorm event at about 0715. Again the motion appears to begin before the onset of the substorm riometer event.

Whistlers observed at 0705 and 0720 UT are shown on the third and fourth panels in Fig-

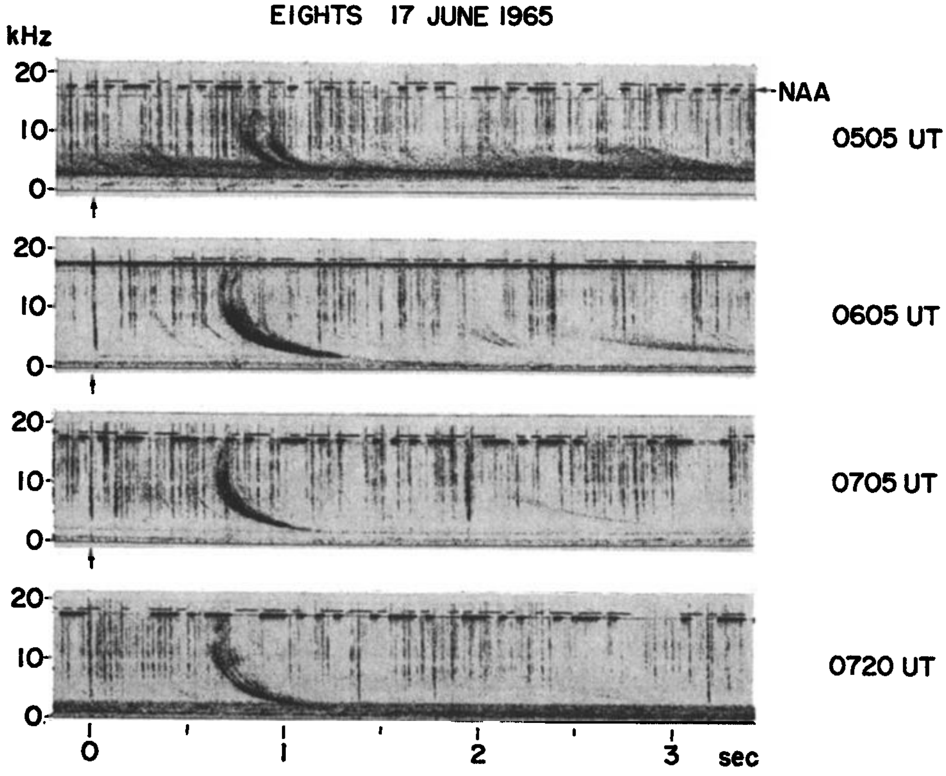


Fig. 3. VLF spectra received at Eights, Antarctica, at several times during the drift activity summarized in Figure 2. The causative impulses of the four events are aligned with the origin of the time scale to facilitate visual comparison. The principal cross-L drift effect appears as a decrease in travel time and increase in nose frequency between the first and second panels, followed in the other panels by similar but smaller changes. See text for details.

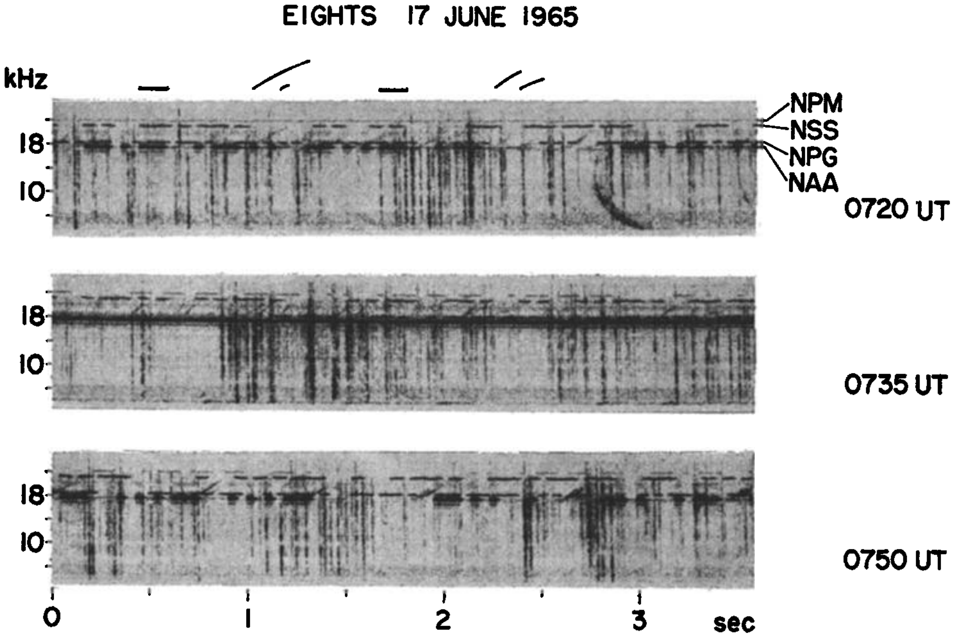


Fig. 4. VLF spectra received at Eights, Antarctica, illustrating triggered noise activity during the drift event of June 17, 1965. Above the top record is a sketch in which are copied 2 NAA dashes and the noises they appear to stimulate on the record just below. The dashes are received after direct propagation under the ionosphere, the triggered noises after whistler mode propagation in the magnetosphere. Fixed-frequency transmissions from various sources are identified at the upper right. The NAA transmission at 0735 UT is FSK, using 17.800 and 17.850 kHz. See text for details.

ure 3. The cutoff frequency f_{co} appears to be very close to the NAA frequency of 17.8 kHz, and it is during this period that triggering of discrete noises begins (X's in Figure 2, bottom). The NAA triggering at 0705 and 0720 is faint and varies in intensity with time, being better defined during parts of the recording period not illustrated in Figure 3 (but rather in Figure 4 for 0720). In Figure 3, faint rising tones above the NAA frequency may be evident on the 0720 panel near $t = 3.1$ sec.

After 0720 UT (0220 LT), the whistler component of interest ceased to be defined sufficiently for continued tracking of the nose frequency. However, evidence from the continuous records indicates that the path or duct persisted until at least 0810 UT, which would be consistent with its having been involved in all four of the successive intervals of observed triggering.

There is little information on plasma drifts after the 't_2' regime reached at ~07–08 UT. Beginning at ~0820 UT, whistler components were observed to propagate on both sides of the plasmapause, and the plasmapause radius appears to be no greater than ~3 R_E. At 0905 UT, the outermost path observed in the plasmasphere is at ~2.8 R_E. Assuming the plasmapause radius to have been slightly greater than 3.1 R_E before 05 UT, the gross behavior of the plasmapause from 05 to 09 UT then appears to have been an inward displacement comparable in amplitude with the whistler path displacement.

Details of Triggered-Noise Activity

The triggering activity indicated by X's in Figure 2 is illustrated in Figure 4 by spectrums (4–25 kHz) from the synoptic recordings of 0720, 0735, and 0750 UT. At 0720 UT (top panel, pairs of faint rising tones are triggered by Morse-code dashes. Sketches above the record indicate representative details of the activity. (At 0705 UT, the activity was similar, but sporadic and of low intensity.) At 0735 UT (middle panel), the FSK transmissions produce many rising tones. This type of triggering is rare, occurring about 3 times less frequently than Morse-code triggering during an equal number of transmission periods. At 0750 UT (bottom panel), Morse-code transmissions again trigger, each dash producing a single relatively intense cluster of noises. At times in this 1-minute run both rising and falling tones occur, of the type described by *Helliwell et al.* [1964] and *Helliwell* [1965]. Triggering was not detected in the next synoptic run at 0805 UT, and recommencement of FSK at 0805 (cf. Figure 2) may have been an important factor in this detail. In any case, NAA triggering was not observed in the synoptic runs of June 17 before 0705 and after 0750 UT.

If the triggering activity is to be associated with the drifting whistler path, then the whistler travel time at 17.8 kHz must be approximately equal to the time from the keying of a Morse-code dash to observation of a stimulated noise. This condition was found to be fulfilled at 0705 and 0720 UT, at which times faint pairs of rising tones followed Morse-code dashes in the manner indicated at the top of Figure 4. The whistler travel time at 17.8 kHz, measured from examples such as those in Figure 3, lower two panels, and Figure 4, top panel, was found to fall between the initial points of the two rising tones, preceding the second tone by 40–100 msec. Allowing for such a delay as part of the triggering process, it is inferred that the second rising tone of each pair propagated on the observed path. Measurements of the noises at 0750 UT suggest that only the equivalent of the second tone was then present. Whistler activity at 0750 UT was insufficient for a precise travel-time comparison.

The lack of an identifiable whistler path for the first noise tone at 0705 and 0720 is not readily explained. However, the paths of the two tones may have been displaced in longitude sufficiently that at 0705 and 0720 UT, NAA could excite them both, but the lightning impulses could not. In any case, the first tone is presumed to be on a path such that $0.4\ f_{H_0} < f_{NAA} < 0.5\ f_{H_0}$, and this is consistent with earlier observations.

The idealized experiment of Figure 1 suggests that magnetospheric whistler-mode propagation of Morse code should accompany the direct subionospheric signals beginning at about 0705 UT when $f_{NAA} \sim f_{co} = 0.5\ f_{H_0}$ (time t_2 in Figure 1). Whistler-mode transmissions of the code are evident on the records during the time of noise activity, but the signals are weak by comparison to the triggered noise. The strongest signals occurred during the 0750 run, when the noises triggered by Morse code were most intense. Extremely faint whistler-mode echoes, of the order of 30 db below the direct NAA signal, were tentatively identified at 0550 UT and at 0905 and 0920 UT. Again the path details are not known, but there is no conflict with the other evidence being considered here.

Discussion and Concluding Remarks

The present case study indicates that triggering occurred at $f_T \sim f_{co}$. The assumption that $f_{co} \sim f_{H_0}/2$ is based on reports referenced in the Introduction, and the evidence of those reports now appears to be reinforced by the self-consistency of the several phenomena reported here.

The calculations relating whistler parameters to magnetospheric coordinates were based on a dipole field model, although the case study refers to conditions just after the main phase of a magnetic storm ($Dst \sim 100\ \gamma$). In a magnetic field dilated but not severely distorted by a ring current, the ratios of the observables f_n and f_{co} to the minimum path gyrofrequency f_{H_0} are not expected to change significantly from their values for an undistorted dipole field (J. J. Angerami, personal communication). Substorm drifts should therefore be detectable in the presence of a symmetric ring current, although absolute values of equatorial radius will be overestimated by some fraction of an earth radius. In the case of Figure 2, corrections for a field dilation would then be largely confined to multiplication of values for path radius by a factor slightly less than 1.

Partial ring currents might be considered as an explanation of changes in whistler nose frequency. Suppose that there is local dumping of ring current particles during a substorm, and a consequent recovery of the geomagnetic field from a dilated condition. Such a recovery should cause an increase in the nose frequency for a whistler duct, without necessarily involving a large change in path equatorial radius. This mechanism appears insufficient to explain the magnitude of the drifts and also many of the temporal details. To explain the change in whistler nose frequency from ~0505 to 0605 UT, a local ring current capable of decreasing the field at 3 R_E by ~150 γ would have to be dumped. Then from ~07–08 UT, the ring current must be dumped again, without apparent replenishment between substorms (i.e., whistler nose frequency did not change appreciably between 06 and 07 UT).

Several concluding remarks are as follows:

(1) In the case study, a well-defined whistler component was continuously monitored for about 3 hours. Its frequency-versus-time properties changed slowly in a manner consistent with propagation in a tube of ionization drifting across magnetic shells near $L = 3$. Travel time decreased with decreasing path equatorial radius ($\Delta R \sim 0.2\ R_E$) and correspondingly increasing nose frequency. The changes occurred in a manner consistent with first-order preservation of the electron content of the drifting tube (see *Carpenter* [1966] and *Angerami and Carpenter* [1966]).

(2) The radial drifts were established 10 minutes or more before the substorm riometer events, and for the first event the inward drift ceased with the initial decay of the substorm. From these and other details it is inferred that the westward component of the magnetospheric electric field associated with this drift was transient, with amplitude ~1 mv/m (at 3 R_E) and duration about 1 hour.

(3) The observations on the ground of VLF noise triggered in the magnetosphere involved the presence of a whistler duct. Well-defined triggering occurred only after the upper cutoff frequency of the duct, inferred from other work to equal half the minimum path gyrofrequency, rose to the approximate level of the transmitter frequency f_T. The triggered noises themselves, once initiated, rose in frequency above f_{co}.

(4) Although the details of the whistler paths are not clear after 08 UT, owing possibly to longitudinal drifts into or out of the 'view' of the ground receiver, whistler paths with $f_{co} > f_T$ were observed after 08 UT, yet no triggering was observed.

The possibility of observing on the ground noises artificially stimulated in the magnetosphere apparently depends strongly on there being an active whistler duct located on the magnetic shell for which equatorial electron gyrofrequency is twice the frequency of the transmitted wave. The probability that this will occur at a given time is low, but the probability that one or more ducts will drift *across* the 'triggering' shell during a substorm is relatively high. This may partially explain our observations (not yet reported) of the occurrence of isolated intervals of triggered noise activity during a number of substorm bay events.

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