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Pulsation Phenomena Observed in Long-Duration VLF Whistler-Mode Signals[1]

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Whistler-mode signals from station NAA (14.7 and 17.8 kHz), Cutler, Maine, show periodic fluctuations ('pulsations') in amplitude and bandwidth. The data were recorded at Eights station, Antarctica, during unmodulated ('key-down') transmissions from NAA lasting up to 2 min. In three of the four instances, the pulsations consist of a series of moderate enhancements of the amplitude and bandwidth of the signal, each pulsation lasting about 50 msec. The fourth instance, however, was unusual in that the key-down signal exhibited remarkably regular and intense amplitude variations. In all four occurrences, the period of the pulsation was in the range from 0.3 to 0.6 sec. In three occurrences, this period was roughly the same as the one-hop whistler-mode delay along the field-line path; however, no demonstrable mechanism to explain this association could be found. An explanation of pulsations in terms of multipath fading effects could not be supported by the data. More likely explanations include intrinsic oscillation in the emission generation mechanism, natural oscillation in the energetic-particle population, or modulation of the VLF growth rate by Pc 1 micropulsations in the region of wave growth.

The early studies of the artificial stimulation of VLF emissions by Morse code transmissions [*Helliwell et al.*, 1964; *Kimura*, 1968; *Lasch*, 1969] established the fact that emissions were triggered almost exclusively by the dashes (150 msec duration) and seldom by Morse dots (50 msec duration). A question unanswered by these early experiments was the behavior of the triggering process when the duration of the triggering signal exceeded the minimum length required for triggering. Under such conditions, it might be expected that many triggerings would occur during the pulse and that any effects associated with the initiation or termination of the pulse could be isolated.

A preliminary study of this question was made by using transmissions on 14.7 and 17.8 kHz from station NAA located at Cutler, Maine ($L \sim 3.2$). The signals were 'key-down' events in which a continuous unmodulated carrier was transmitted for periods of up to 2 min. Both ground-wave and whistler-mode components were received in the conjugate region at Eights station ($L \sim 4$) in the Antarctic. It was found that the whistler-mode component of the key-down signal tends to settle into a remarkable pulsation pattern lasting 10 sec to 1 min or so and having a fundamental frequency of about 2 to 3 Hz.

Observations

A search through 100 hours of Eights station broad-band data recorded in the period from 1963 to 1965 has revealed seven examples in which key-down transmissions were received. In analyzing each key-down event, two methods were employed. First, broad-band spectral records of frequency versus time were prepared to get an over-all view of the emission activity. Second, narrow-band records of the amplitude of the NAA signal as a function of time were also prepared. These narrow-band records were made by passing the output from the broad-band tapes through a 200-Hz bandpass filter centered at the NAA frequency. The filter output was then used as input to a chart recorder. The narrow-band amplitude data are necessary in analyzing key-down events since the particular type of broad-band spectra used in this study

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gives little information on amplitude variations. Of the seven examples obtained, three involve only ground-wave signals with no evidence of whistler-mode components. The other four examples show definite evidence of the presence of both a ground wave and a whistler-mode wave component. In all four instances, the whistler-mode component tended to settle into a pulsation mode in which periodic modulations of the signal (period ~0.5 sec) would occur over time spans of 10 sec or more.

In three of the four instances in which modulation was observed, the periodic modulation was relatively weak, each modulated portion consisting of a short segment of the NAA key-down signal (~50 msec) in which the signal amplitude and bandwidth were moderately enhanced. We refer to these periodic modulations as 'pulsations.'

In general the pulsations occurred in groups consisting of 10 to 40 elements, with two or more of these groups appearing during the key-down transmission. In each instance the period between the pulsations was constant to within 15%. Since broad-band data recorded at ground stations in the northern hemisphere during these key-down events reveal no periodic modulations of the ground-wave signal, it can be concluded that the pulsations are definitely not produced by variations in the NAA transmitter power or frequency output. In addition to the pulsations, numbers of weak emissions could be seen during the key-down events. These emissions appeared to be triggered by the key-down signals but did not occur simultaneously with the pulsations. The time interval between these emissions varied widely but was always much smaller than the pulsation period in each key-down event. (See Table 1).

The fourth modulated event was markedly different from the other three in that the periodic modulation was quite strong and persisted throughout almost the entire period of the key-down signal. Figure 1 shows the amplitude records for this event, recorded at Eights station during the local postsunrise period (1135 UT) on September 12, 1965. Expanded chart records (not shown) of this event show that the ground wave arrives at Eights about 550 msec (the approximate one-hop whistler-mode delay) before the whistler-mode wave. They also show that the ground-wave amplitude is down about 20 db with respect to the whistler-mode wave. (Low values of ground-wave amplitude are common in the postsunrise period.) Thus for all practical purposes the amplitude shown in Figure 1 can be considered as the amplitude of the whistler-mode signal alone.

The key-down transmission is received at Eights a few seconds after the start of the synoptic recording period, the first few seconds of the recording period consisting of Morse code traffic. The key-down portion of the record is most remarkable. It shows that the whistler-mode key-down signal is not only subject to large fluctuations in amplitude, but that these fluctuations settle down into a precise periodic mode after an initial period of disorder. (No behavior of this sort was seen in the Byrd station recording of NAA or in the recordings

TABLE 1. Some Pertinent Details of Four Pulsation Events Detected at Eights Station in 1963 and 1965

Time	$\sum K_p$	f_{NAA}, kHz	Pulsation Period, msec	Time Interval between Emissions, msec	Whistler-Mode Delay, msec
April 7, 1963, 0250 UT	12 (16)	14.7	470 ± 10	100 ± 20	450 ± 20
June 18, 1963, 1450 UT	26 (18)	14.7	440 ± 20	90 ± 20	590 ± 20
Aug. 1, 1963, 0150 UT	25 (26)	14.7	330 ± 10	80 ± 20	440 ± 150
Sept. 12, 1965, 1135 UT	17 (7)	17.8	570 ± 10	none observed	580 ± 20

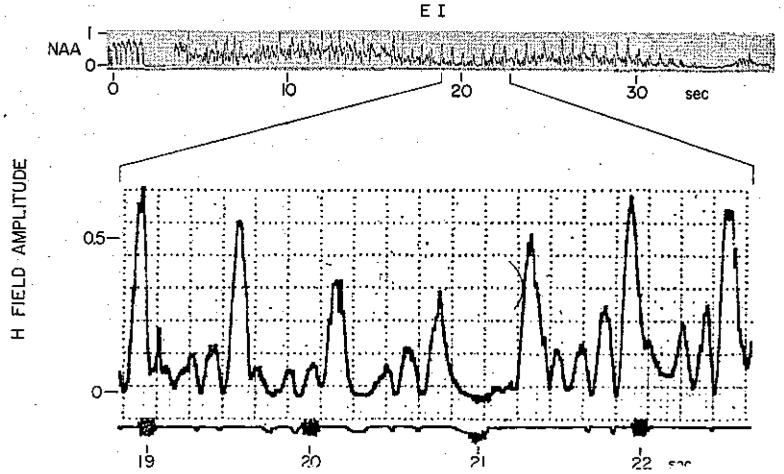

Fig. 1. Relative amplitude of key-down signal (17.8 KHz) transmitted from station NAA, Cutler, Maine, September 12, 1965, at 1135 UT. Transmission recorded at Eights station, Antarctica.

of NPG, Jim Creek, Washington, at 18.6 kHz at either Eights or Byrd. Byrd station is in the Antarctic, approximately 1000 km from Eights.) An important feature of this periodic mode is the set of subsidiary peaks that lie between the maximums. In the latter part of the record, there are several sets showing exactly three subsidiary peaks between the main peaks. Their spacing is about 140 msec. In some instances (e.g., 21–22 sec), the amplitude trace is suggestive of an exponentially increasing sinusoid.

An idea of the constancy of the period between major amplitude peaks in Figure 1 can be obtained from Figure 2, which is a plot of time delay (from the 12-sec mark of Figure 1) of each major peak, numbered consecutively. A fixed period would result in all the points falling on the same straight line. It can be seen from the figure that the deviations from a straight line are small but that the period appears to oscillate slowly. It is an interesting feature of this event that within experimental error the average pulsation period is equal to the (measured) one-hop whistler-mode delay of the main signal. However, it is also notable that the pulsation period is distinctly more irregular than the period found in long-enduring whistler-echo trains [*Helliwell*, 1965, p. 301].

DISCUSSION

Table 1 summarizes some of the pertinent details of the four pulsation events. For each event we show the Kp sum for the day of the event, the Kp sum for the day preceding the event (in parentheses), the transmitter frequency, the period of the observed pulsation, the time interval between emissions, and the one-hop whistler-mode delay time.

The one-hop whistler-mode delay time was determined either by direct measurement of the delay between the ground- and whistler-mode components of the NAA signal (June 18, 1963 and September 12, 1965 events) or by measurements of the travel time of whistlers believed to be traversing the same field-aligned path traveled by the NAA signal (May 7, 1963 and August 1, 1963 events). The time interval between emissions was determined by taking an average of the time delay between all triggered emissions that occurred during the key-down event.

It can be seen that two of the events occurred during magnetically quiet periods, whereas the other two occurred during moderately disturbed periods. Our most striking example, that of September 12, 1965, occurred at the end of a very long quiet period that was interrupted by a substorm about 8 hours before the pulsation event.

The pulsation periods vary from 300 to 600 msec, and, with the exception of the June 18 event, the pulsation period is equal to the one-hop whistler-mode delay, within experimental error. (In one instance the experimental error is quite large.)

Our results raise the interesting possibility that the pulsation period is controlled by the one-hop whistler-mode delay. If this possibility is true, it is most unusual. There are many periodic-emission phenomena that are known to occur at the two-hop whistler-mode delay but so far none have been reported at the one-hop delay. One type of periodic emission that gives the appearance of occurring at the one-hop delay is the symmetrical two-phase periodic emission [*Helliwell,* 1965]. This type is very rare, but it is conceivable that the key-down events do settle into the two-phase pulsation mode and that the pulsations do occur at the one-hop whistler-mode delay.

On the other hand, the close correspondence between the pulsation period and the whistler-mode delay may be entirely coincidental. If this is the case, other possible explanations of the pulsations arise. One possibility is that the pulsations might be related to particle-bounce times or to precipitation phenomena. The existence of pulsations in precipitating particle flux is well known. For instance, *Oliven et al.* [1968] reported groups of electron microbursts at $L \gtrsim 6$ with periods of about ½ sec. Similar microbursts have been seen in association with VLF emissions [*Oliven and Gurnett,* 1968]. *Evans* [1967] reported 100-msec periodicities in precipitating auroral elections in the range from 1 to 100 kev. *Omholt and Berger* [1967] reported auroral pulsations with a 100-msec period. Modulations in the energetic-particle population of this nature could conceivably lead to the modulation of the intensity of some existing magnetospheric instability mechanism that was affecting the key-down signal amplitude.

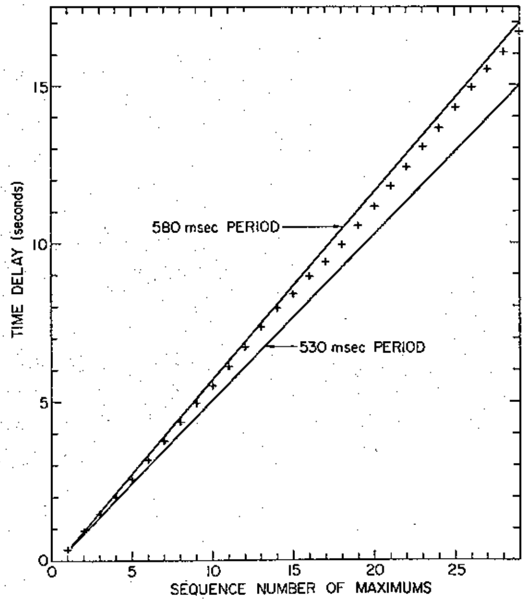

Fig. 2. Plot showing total time delay of each major amplitude maximum in key-down transmission versus sequence number of this maximum on September 12, 1965, at 1135 UT. The time delay and sequence number are referenced to the 12-sec mark of Figure 1.

Another possibility is that the pulsations in the key-down signal are the result of a modulation impressed on the particle population by a second wave that is present along the field-line path. For instance, a Pc 1 micropulsation event was recorded in the 0.1-Hz channel at Eights during the September 12 pulsation event. Since no routine recordings of Pc 1 events were made at Eights in the 2-Hz range, it cannot be said for certain that activity was present at these frequencies, but it might be hypothesized that a 2-Hz Pc 1 micropulsation was propagating along the field lines during the key-down. This micropulsation could periodically modulate the velocities of the resonant-particle population. In turn, this modulation could affect the growth rate of some existing instability, the effect being a key-down signal modulated in amplitude and frequency at the micropulsation frequency. However, it is not clear that any large change in instability growth rate would occur unless the amplitude of the micropulsation was large.

Still another possibility is that the pulsation is a property of the instability process itself. It is likely that we are dealing with a feedback process [*Helliwell,* 1967], and it is possible that low-frequency oscillations occur as the result of fluctuations in the feedback loop, somewhat like the 'motor-boating' phenomenon seen in electronic feedback amplifiers.

If this hypothesis is true, the distribution of field intensity in the September 12, 1965, event should yield information concerning the instability mechanism. In particular, the presence of deep nulls approximately every 140 msec would suggest that stimulated wave components have been produced whose amplitudes (A_s) are approximately the same as the NAA carrier amplitude (A_{NAA}) but whose frequency is offset by about 7 Hz. The depth of the fading could be explained either by double–side-band modulation ($A_s \approx \frac{1}{2} A_{NAA}$) or single–side-band modulation ($A_s \approx A_{NAA}$).

Another explanation of the observed pulsation phenomena is multipath interference. To explain deep nulls in this manner, we need at least two whistler-mode signals traveling over separate field-aligned paths whose relative phase delays vary with time. Such variation might be caused by $\mathbf{E} \times \mathbf{B}$ duct convection, periodic electron-density changes in the F_2 region, etc. Strong fading attributed to multipath propagation has been observed [*Helliwell*, 1965], but the fading period is of the order of 10 to 100 sec, far greater than the pulsation periods reported here. Furthermore, multipath fading effects are, in general, not regular in time, their irregularity contrasting sharply with the regularity displayed by the September 12 event. Finally, the absence of deep fading in the Morse code signals preceding and following the September 12 event would require that multipath fading take place only during the key-down transmission. For these reasons, we believe that the hypothesis of multipath fading is the least tenable of the explanations advanced above.

It should be noted here that *McNeill* [1968] has reported a process of whistler-mode amplification that is connected with key-down signals from NPG at 18.6 kHz. McNeill's studies showed that on many occasions the amplitude of the NPG whistler-mode signal (30-sec time-averaged amplitude) was seen to be higher after a key-down transmission than it had been before the transmission. The enhancements were seen to persist with a time constant of about 50 min, and on some occasions the enhancement was as large as 10 db.

McNeill [1968] was able to show that these amplitude enhancements were not a result of variations of transmitter power and concluded that the phenomenon resulted from an amplifying mechanism in the magnetosphere.

It is conceivable that the amplification phenomenon reported by *McNeill* [1968] may be connected in some way with the pulsation phenomenon we have reported here. However, it is difficult to compare the two sets of data. For instance, as a result of the 30-sec averaging that took place in McNeill's experiment, it is not possible to determine if pulsation phenomena actually occurred during the key-down signals he observed. Furthermore, McNeill reports his amplification events as being predominantly a sunset phenomenon, whereas our strongest example occurred in the postsunrise period.

It is clear that many more examples of pulsation events must be obtained before we can make a meaningful comparison between *McNeill's* [1968] data and our own.

CONCLUSIONS

In a study of seven NAA key-down events, we have found a definite tendency for whistler-mode signals of long duration and fixed frequency to settle into a periodic-pulsation mode in which the pulsation period is quite regular. The pulsation period may be related to the one-hop whistler-mode delay. On the other hand, it could also be related to natural oscillations in the energetic-particle population, to the presence of Pc 1 micropulsations, or to an intrinsic oscillation in the emission-generation mechanism.

It is important to note that the pulsation events reported here apparently represent a phenomenon completely different from that reported in earlier studies of artificially stimulated VLF emissions. These early studies dealt with instances in which a short signal (Morse code dashes) of constant frequency and of relatively constant amplitude triggers an emission whose average center frequency differs markedly from the frequency of the triggering pulse.

On the other hand, each of the pulsation events reported here occurs without the simultaneous appearance of an emission and at essentially fixed frequency. As a result of these characteristics, the type of amplitude variation shown in Figure 1 will be useful in studying the nonlinear transfer function of VLF signals propagating through the magnetosphere.

If the key-down pulsation found in this study is the result of a wave-particle interaction (as seems likely), our data can be used to test contemporary theories of VLF wave-particle interactions. In this regard, the explanation of the event shown in Figure 1 would appear to be far beyond the purview of the linear theory of cyclotron-resonance interaction, as presently developed. (See, for instance, *Liemohn* [1967].)

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