JOURNAL OF GEOPHYSICAL RESEARCH VOL. 69, NO. 11 JUNE 1, 1964

Artificially Stimulated Very-Low-Frequency Radiation from the Ionosphere

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In the course of experimental studies of whistlers and related ionospheric effects conducted by Stanford University, a new phenomenon has been discovered. It is the triggering of VLF emissions in the ionosphere by whistler-mode signals transmitted from VLF stations operated by the U. S. Navy. Although much remains to be learned about this remarkable phenomenon, certain important features are already sufficiently clear to warrant reporting at this time.

Evidence of triggered emissions was first found on the IGY-IGC synoptic tape recordings made at Wellington, New Zealand, on November 28, 1959, at 0835 UT [*Helliwell,* 1962]. A spectrum analysis, from 15 to 35 kc/s, of a short section of that record is shown in Figure 1. The triggering signals, Morse code transmissions from station NPG (Jim Creek, Washington), can be seen as a broken line at 18.60 kc/s on the spectrogram. The emissions consist mainly of rising tones (called 'risers') lasting about 0.1 or 0.2 sec. Analysis of the starting time of each of these risers with respect to the transmitted Morse code characters showed that the risers were associated with 96 per cent of the dashes and only 4 per cent of the dots.

Also appearing on the spectrogram of Figure 1 are the upper parts of a strong whistler-echo train, whose two-hop travel time at 18.60 kc/s is about 1.10 sec. Whistler-mode propagation was also observed on the NPG Morse code transmissions themselves, and the echo delay was found to be 0.55 sec, which is the same as the one-hop delay of the whistler at 18.6 kc/s. The starting time of the triggered emission with respect to the leading edge of the transmitted pulse averaged between 0.62 and 0.68 sec. Thus the emissions were initiated between 70 and 130 msec after the beginning of the whistler-mode echo from the NPG pulse.

Better examples of artificially triggered VLF emissions were recorded during synoptic-recording schedules on the United States Antarctic Research Program's research ship USNS *Eltanin* while it was cruising off Palmer Peninsula at 51.5°S geomagnetic latitude on October 19, 1962. Each of the two-minute runs at 0850 and 1050 UT showed strong discrete emissions that were associated with the dashes, but not the dots, transmitted by Station NAA (Cutler, Maine) operating on 14.70 kc/s. Whistler-mode echoes from NAA were observed in both runs. A short section of each of these records is shown in the upper sections of Figures 2 and 3; in the lower sections are shown the corresponding spectrums obtained simultaneously at another station, Great Whale River (GWR), where the subionospheric, or direct, wave is well defined. The GWR records have been shifted to the right by about 0.66 sec in Figure 2 and 1.23 sec in Figure 3 so that the dashes fall approximately under their associated emissions. Figure 2 shows eight transmitted dashes and seven transmitted dots from the 0850 UT run. Associated with each dash is a strong, well-defined discrete emission. Figure 3 shows six transmitted dashes and twelve transmitted dots from the 1050 UT run. As in the 0850 UT run the association between emissions and dashes is the same. However, the emission pattern differs significantly. In all cases shown in Figure 3, both rising and falling tones are associated with the same dash. In a few cases the emission consists of a tone which first falls and then rises in frequency. A good example of this form, commonly called a hook, appears on the record of Figure 3, beginning at approximately 50.3 sec and lasting nearly 1 sec.

The two-minute run obtained at 0950 UT on October 19, 1962, was also examined, but no strong artificially stimulated emissions were observed. However, the spectrogram of the NAA signals showed slight broadening at delays comparable with the whistler-mode echo delay, indicating that only a relatively weak instability

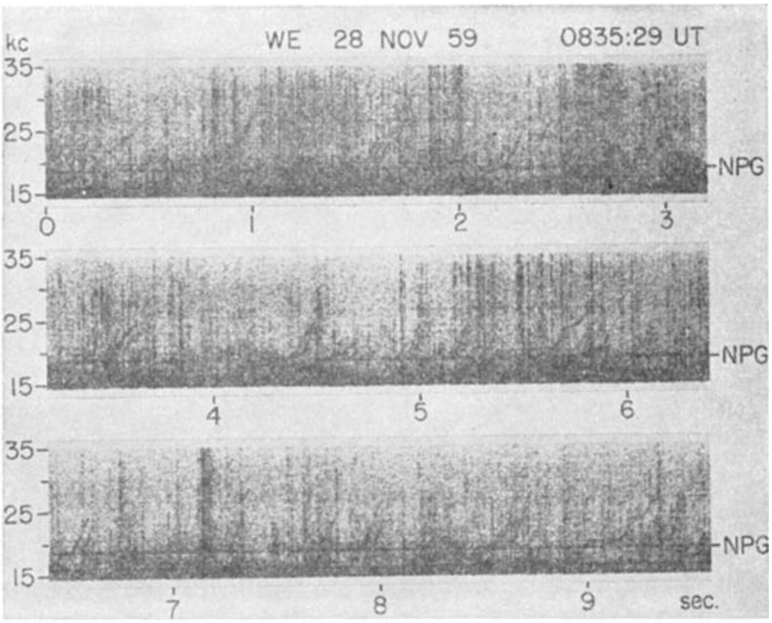

Fig. 1. Rising tones triggered by the whistler-mode echoes from the Morse code dashes being transmitted by station NPG (18.60 kc/s). These were recorded in Wellington, New Zealand, on November 28, 1959, during the 0835 UT whistler-synoptic-recording schedule.

was present at 14.7 kc/s in that hour. At frequencies of 3 to 4 kc/s on this same run, risers triggered by whistlers were observed, indicating that the optimum frequency for the triggering of emissions had dropped during the intermediate hour.

During the 0850 UT run a multipath whistler (not shown) was observed, the strongest component of which showed a travel time of 0.646 sec at 14.7 kc/s. Allowing a nominal 30 msec for the travel time of the direct pulse from NAA to the *Eltanin,* the measured delay of the beginning of the strong emission with respect to the leading edge of the transmitted dash is found to average 0.765 sec. Assuming that the emissions were triggered by whistler-mode sig-

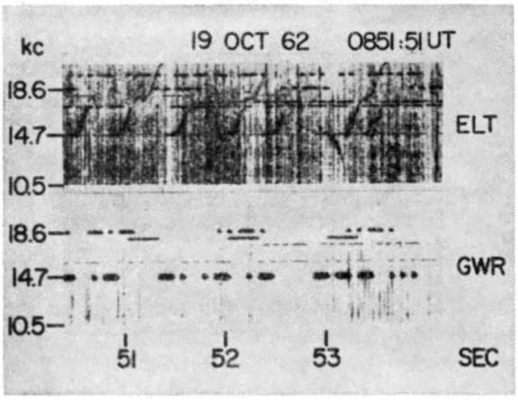

Fig. 2. Rising and falling tones triggered by the whistler-mode echoes from the Morse code dashes being transmitted by station NAA (14.70 kc/s). These were recorded aboard the *Eltanin* on October 19, 1962, during the 0850 UT whistler-synoptic-recording schedule.

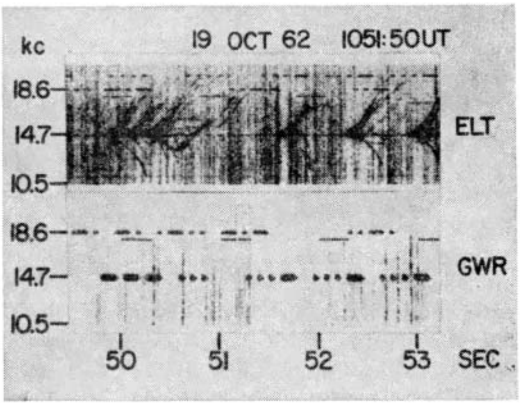

Fig. 3. Simultaneous rising and falling tones triggered by the whistler-mode echoes from the Morse code dashes being transmitted by station NAA (14.70 kc/s). These were recorded aboard the *Eltanin* on October 19, 1962, during the 1050 UT whistler-synoptic-recording schedule.

nals having the same delay as the strongest whistler component, the triggering delay is then found to be 119 msec with respect to the leading edge of the whistler-mode echo from the NAA dash.

From multicomponent whistlers (not shown) observed during the 1050 UT run, the travel times at 14.70 kc/s were found to range from 1.08 to 1.165 sec. The measured delay of the earliest emission, averaged over the two-minute run, was 1.218 sec with respect to the direct wave. Thus the delay of the first emission with respect to the first whistler-mode echo is 138 msec.

In all three runs each dash is frequently associated with more than one discrete emission. The differences in their delays appear to remain constant during a run. Since multiple-path whistlers were recorded in all cases, these differences in delays might be attributed to triggering over separate paths having different travel times. The results of this analysis will be reported in a subsequent paper.

The results described above are summarized in Table 1, which shows the whistler-mode delay and the average triggering delay of the strongest emissions, together with the difference in these delays. The durations of the Morse code characters are shown for comparison.

From the association of the emissions with the whistler-mode rather than the direct signals, we conclude that triggering takes place somewhere along the whistler-mode path. From the association of the emissions with dashes rather than dots, we conclude that the duration of the triggering signal must exceed a certain critical value before any effect is produced. We might expect the intensity of the transmitted signal to be an important factor, and certainly the intensity must exceed some minimum value to cause triggering. However, in view of the consistency of these observations for such widely different circumstances of geography, time, and transmitter power, it would appear that, for signals exceeding a certain minimum intensity (not yet known), the duration of the signal is the dominant factor in determining the production of an emission. On the basis of these few data, we estimate the triggering time to be of the order of 100 msec.

From the observations described above we can draw several conclusions. First, fixed-frequency VLF signals exceeding a certain minimum duration are capable of producing a variety of discrete emissions including risers, falling tones, hooks, and more complex forms. Second, during these particular periods of triggered-emission activity, emissions were produced whenever a suitable signal was transmitted. Therefore the generation mechanism apparently does not require the presence of a short-lived set of conditions, such as a small bunch of charged particles trapped in the earth's magnetic field. This result supports the conclusions drawn from an analysis of whistler-triggered periodic VLF noise [*Helliwell*, 1963]. Although the details of the emission mechanism are not yet understood, it seems clear that the mechanism must involve some highly nonlinear interaction between the passing wave packet and the medium. These

TABLE 1

Date	Length of Transmitted Dot, sec	Length of Transmitted Dash, sec	Whistler-Mode Delay, sec	Average Triggering Delay of Strongest Emissions, sec	Time from Beginning of Whistler-Mode Echo to Initiation of Emission, sec
Nov. 28, 1959 0835 UT	0.045	0.145	0.550	0.620–0.680	0.070–0.130
Oct. 19, 1962 0850 UT	0.045	0.145	0.646	0.765	0.119
Oct. 19, 1962 1050 UT	0.045	0.145	1.080	1.218	0.138

emissions might well be related to the transverse instability in the interaction between whistler-mode waves and a moving stream as suggested by *Brice* [1963] and developed by *Bell and Buneman* [1964].

Because of the reproducible and quantitative nature of these observations, we suggest that they could profitably be extended through the planned use of man-made triggering sources operating at substantially lower frequencies (about 5 kc/s). With a VLF transmitter whose power, frequency, and modulation could be controlled, the effect of signal parameters on the occurrence and form of emissions could be studied, one at a time. For example, we would like to know the effects of pulse length, spacing between pulses, carrier frequency, change of frequency with time, and level of radiated power. The optimum frequency range for these suggested experiments is believed to be much less than those used in the present observations. From studies at Byrd Station and elsewhere, it appears that frequencies in the range from 2.0 to 6.0 kc/s would be most suitable.

Controlled experiments on artificially stimulated VLF ionospheric emissions would greatly extend our knowledge of the interactions between electromagnetic waves and plasmas. In particular, they may lead to a quantitative understanding of the origin of discrete VLF emissions, such as the dawn chorus. Understanding of VLF emission may in turn lead to new tools for study of the magnetosphere and the causes of various auroral and geomagnetic phenomena.

Acknowledgments. Helpful comments were contributed by T. F. Bell and D. L. Carpenter.

This work was supported in part under contract Nonr 25(27), monitored by the U. S. Navy, Office of Naval Research, in part by National Science Foundation grants G18560 and GA-79, and in part by the Air Force Office of Scientific Research grant AF-AFOSR-62-370.

REFERENCES

Bell, T. F., and O. Buneman, Plasma instability in the whistler mode caused by a gyrating electron stream, *Phys. Rev.*, *133*(5*a*), 25–36, 1964.

Brice, N., An explanation of triggered very-low-frequency emissions, *J. Geophys. Res.*, *68*(15), 4626–4628, 1963.

Helliwell, R. A., Artificially stimulated VLF electromagnetic radiation from the earth's atmosphere, paper presented at URSI/IRE meeting, Ottawa, Canada, October 1962.

Helliwell, R. A., Whistler-triggered periodic very-low-frequency emissions, *J. Geophys. Res.*, *68* (19), 5387–5395, 1963.

(Received February 28, 1964.)