Whistler-Induced Amplitude Perturbation in VLF Propagation*

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Sudden changes in the amplitude of long-distance subionospheric VLF transmissions have been found at night in association with whistlers. Both increases and decreases in signal strength have been observed, depending on signal frequency and orientation of the receiving antenna. Sample observations at Eights Station in Antarctica of station NSS (Annapolis, Maryland) on 22.3 kHz showed increases in signal strength that averaged 3 db, with rise times of about 2 sec and durations of about 30 sec. Coincident with every rise was a midlatitude ($L \approx 2.5$) whistler originating in the northern hemisphere. To explain this association, it is suggested that the whistler dumps energetic (30–300 kev) electrons into the D region. The resulting ionization then alters the properties of the earth-ionosphere wave guide. The mechanism of precipitation is thought to be pitch angle scattering of trapped electrons that resonate with the magnetic field of the whistler wave near the magnetic equator.

The purpose of this note is to report an association between whistlers and long-distance VLF propagation. It is found that certain sudden increases or decreases in the amplitude of a VLF signal coincide with the reception of a midlatitude whistler. These amplitude anomalies have been observed at all local nighttime hours, with the highest rates (~30/hour) usually occurring between midnight and dawn. Every anomaly was directly associated with a whistler produced by a lightning discharge. This association was observed by one of us (MLT) during his year-long (1963) stay at Eights Station, Antarctica.

We suggest that the anomalies result from D region ionization produced by whistler-induced precipitation of energetic ($E > 30$ kev) electrons. The interaction is postulated to occur near the equatorial plane where the electrons are in cyclotron resonance with the whistler for an extended period of time. This interpretation is supported by the recent observation of an association between bursts of X rays ($E > 30$ kev) and discrete VLF emissions triggered by whistlers [*Rosenberg et al.*, 1971].

* The principal results of this paper were first presented at the meeting of Commission IV of the U.S. National Committee of URSI held in Los Angeles, California, in September 1971.

Observations. The data presented in this paper were acquired at Eights Station, Antarctica (75°S, 77°W, geographic; 64°S geomagnetic), over the period October 3 through November 2, 1963. Several channels of narrow-band data were recorded on a multichannel chart. These included the relative amplitudes of station NSS (Annapolis, Maryland) at 22.3 kHz from two orthogonal loops, and station NAA (Cutler, Maine) at 18.6 kHz. Whistlers and other natural noise at 2.9 kHz were recorded on a fourth channel. Broad-band amplitude recordings in the range 0.3–30 kHz were made on magnetic tape at 50–52 min past each hour. On occasion, continuous broad-band magnetic tape recordings were made in the range 0.3–10 kHz. Most of the phenomena observed at Eights were also observed at Byrd Station, Antarctica (80°S, 120°W, geographic; 71°S geomagnetic). However, the intensities of the whistlers at Byrd were generally less than at Eights. The locations of the transmitters and receivers are shown on the map of Figure 1.

An example of the perturbation events, observed at both Eights and Byrd, is shown in Figures 2 and 3, respectively. At this time NSS was transmitting a 200-msec pulse every 2 sec. The whistler spectrum is shown at the top of each figure. From expanded spectra (not shown), it was found that the strong whistlers generally show several multipath components, typical of whistler activity at Eights and Byrd

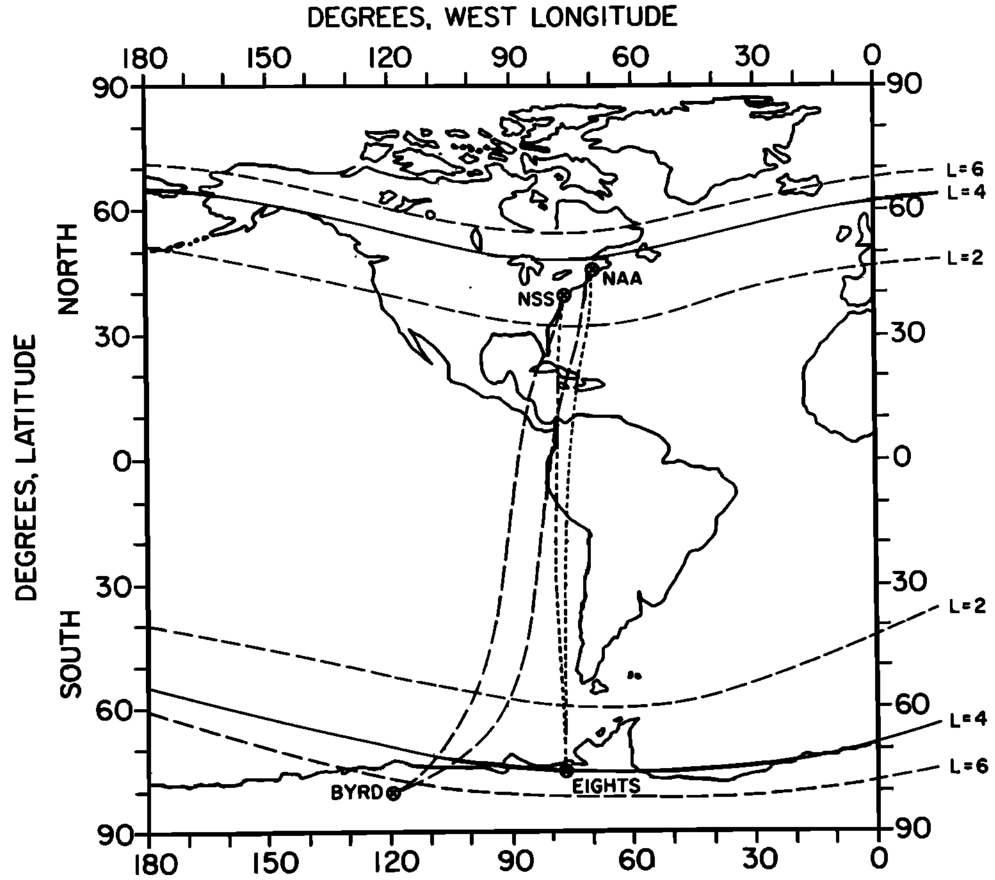

Fig. 1. Map showing NAA, NSS, Eights, and Byrd Stations. Dashed lines represent great circle paths.

Stations. Their path latitudes range from near 50° to more than 60° geomagnetic latitude; the strongest trace corresponds to $L = 2.5$ and an equatorial electron density of about 1800 el/cc (D. L. Carpenter, private communication). The middle panels of both Figures 2 and 3 show the integrated VLF intensity in the 2- to 6-kHz band where the whistlers reach their maximum intensity. It is seen that the strongest whistler signals, near the center of the record, appear in the 2- to 6-kHz band at the same time that the amplitude of NSS increases by a factor of about 2. The whistler amplitude trace shows two main peaks in intensity that correspond to two multipath whistler groups excited by separate lightning impulses spaced 2 sec apart. Other weaker whistlers can be seen, each accompanied by a less well defined rise in the amplitude of NSS. Station NBA (18.0 kHz) located in the Canal Zone was recorded on the same tape but showed no perturbations at the times of the whistlers. Likewise there were no appreciable changes in NAA at the times of these events.

On another occasion, illustrated in Figure 4, NSS again showed increases in amplitude coincident with the reception of whistlers. In addition, each of the two largest enhancements of NSS shown in Figure 4 is accompanied by a small decrease in the amplitude of NAA at 18.6 kHz. Furthermore, there are long-enduring whistler echo trains in the range 2–3 kHz, thus suggesting cyclotron resonance amplification of the whistlers by energetic electrons.

Further evidence of the association between NSS amplitude enhancements and whistlers is shown in Figure 5. The amplitudes of NSS and whistlers at 2.9 kHz are shown in parts a and b,

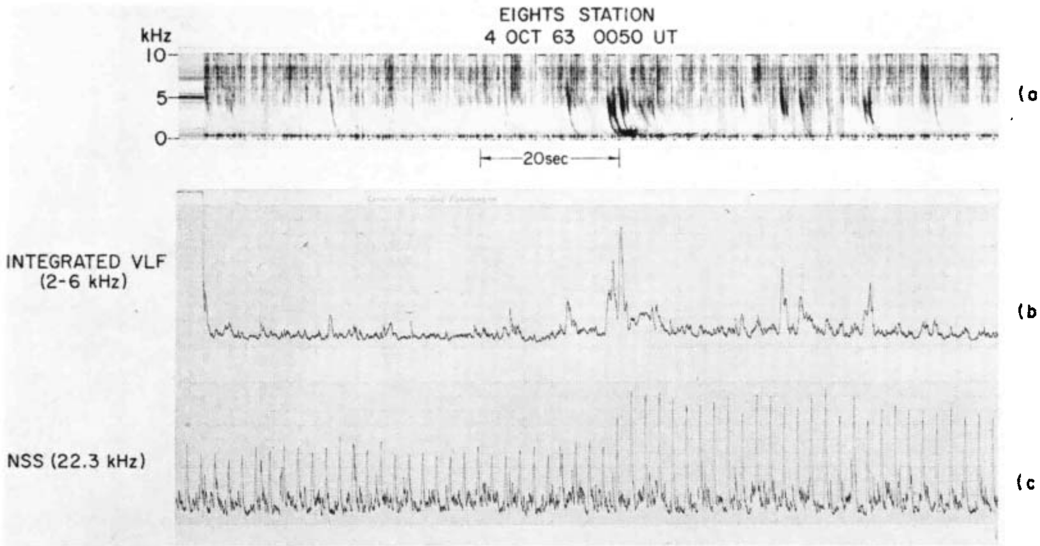

Fig. 2. (*a*) Whistler spectra; (*b*) whistler amplitude, 2–6 kHz; and (*c*) NSS pulse transmissions, observed at Eights Station.

respectively. Spectra of some of the whistlers appearing on the chart of part *b* are shown in part *c* and again in a more expanded form in parts *d* and *e*. Roughly 15 enhancements of NSS can be identified in part *a*. Each coincides with a whistler pip appearing in part *b*. All perturbations shown in part *a* were associated with pips on the 2.9-kHz channel and with whistler traces on the spectral displays. All the whistlers showed multiple-path components. As in Fig-

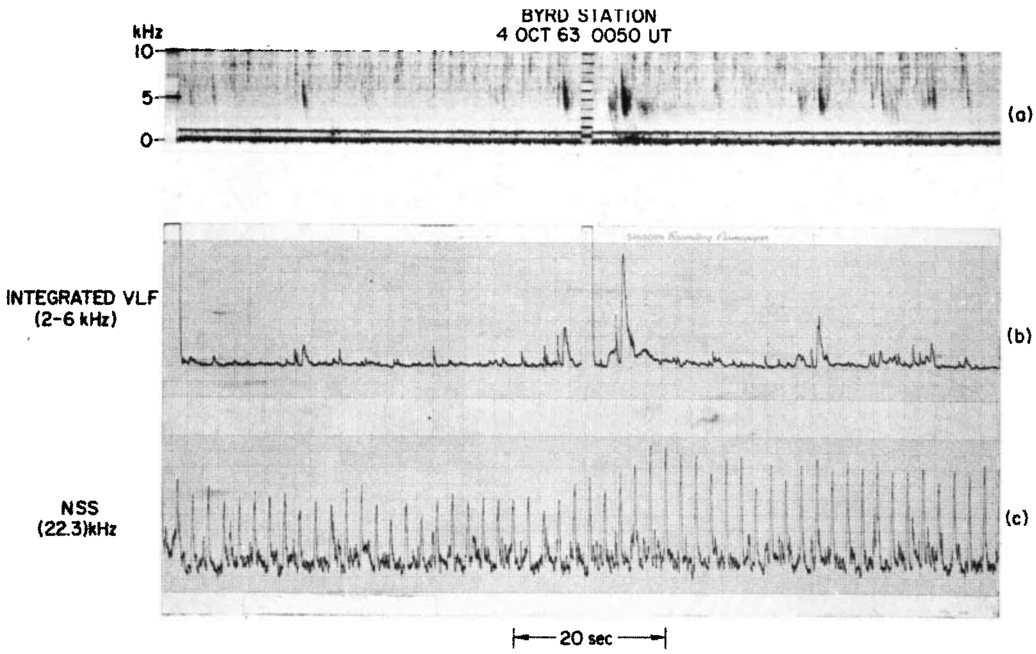

Fig. 3. (*a*) Whistler spectra; (*b*) whistler amplitude, 2–6 kHz; and (*c*) NSS pulse transmissions, observed at Byrd Station.

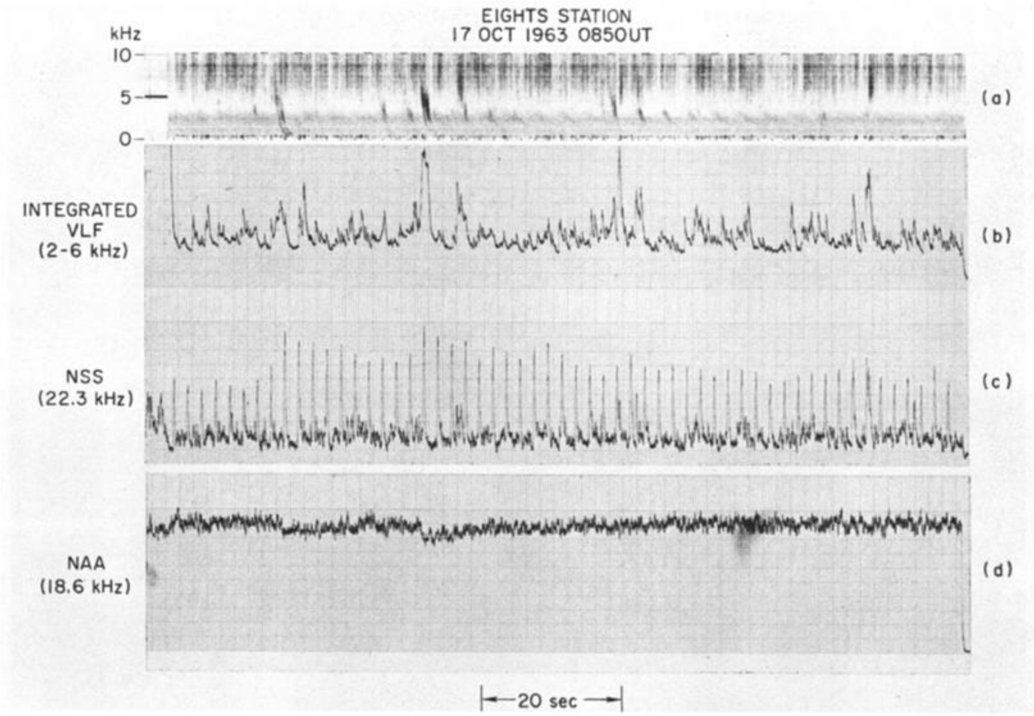

Fig. 4. (*a*) Whistler spectra; (*b*) whistler amplitude, 2–6 kHz; (*c*) NAA pulse transmissions; and (*d*) NSS key down amplitude.

ures 2, 3, and 4 the weaker whistlers produced little or no effect on the NSS signal.

The effect of the orientation of the receiving loop is shown in Figure 6. The whistler pips recorded in the 2.9-kHz channel are shown in part *a*. The corresponding enhancements in the amplitude of NSS as received on loop 1 are shown in part *b*. (Loop 1 is aligned along the local magnetic meridian, which, for Eights Station, is 41° east of true north. Loop 2 is perpendicular to loop 1.) Each enhancement begins with a fast (1–3 sec) rise in amplitude of up to 6 db, followed by a slower recovery lasting 10–40 sec. The same signal as received on loop 2 is shown in part *c*. There the perturbations are similar in form but opposite in sense. However, the perturbations observed on loop 2 are detectable only during the first 30 min of the record. During the last 10 min four large perturbations are seen on loop 1 but none on loop 2. The fact that the amplitude increases on one antenna and decreases on the other suggests that these particular perturbations may result from a change in polarization or a change in direction of arrival. However, other examples have been found in which both loops show an increase, thus suggesting an actual increase in total field intensity at the receiver.

The effect of frequency on the perturbations is further illustrated by the records of NSS on 22.3 kHz and NAA on 18.6 kHz shown in Figure 7. Enhancements occur on NSS, as in Figure 6*b*, while NAA shows only attenuation. This difference may be related to the antenna orientation effect just described because polarization is dependent on frequency.

Some statistics on the perturbations were obtained from records showing high rates over several hours. Each event was scaled for the beginning and end of the rise, the amplitude of the rise, and the half-life of the recovery. Mean values of rise time, the half-life, and the enhancement factor for the selected days are given in Table 1. The average rise time is 2.1 sec, with values of up to 8 sec. This spread in rise time appears to result mainly from the superposition of closely spaced whistler events. The minimum rise time may be less than 1 sec, as suggested by the two negative perturbations on NAA shown in Figure 4*d*. The half-life of the perturbation averages 30 sec and ranges from less than 10 to 70 sec. However, many of the individual values are uncertain because of the difficulty in estimating the background level, which itself varies with time. Also, the superposition of events is hard to detect.

It has been noted that the onset of each amplitude perturbation coincides with a whistler. However, not every whistler is associated with a perturbation. In fact, there are nearly ten times as many detectable whistlers as there are amplitude perturbations. Although the reasons for this difference are not entirely clear, two possibilities can be suggested. First, the recovery time of the perturbation is an order of magnitude greater than the rise time. Thus the perturbation effect of many of the whistlers could be masked by a previous perturbation

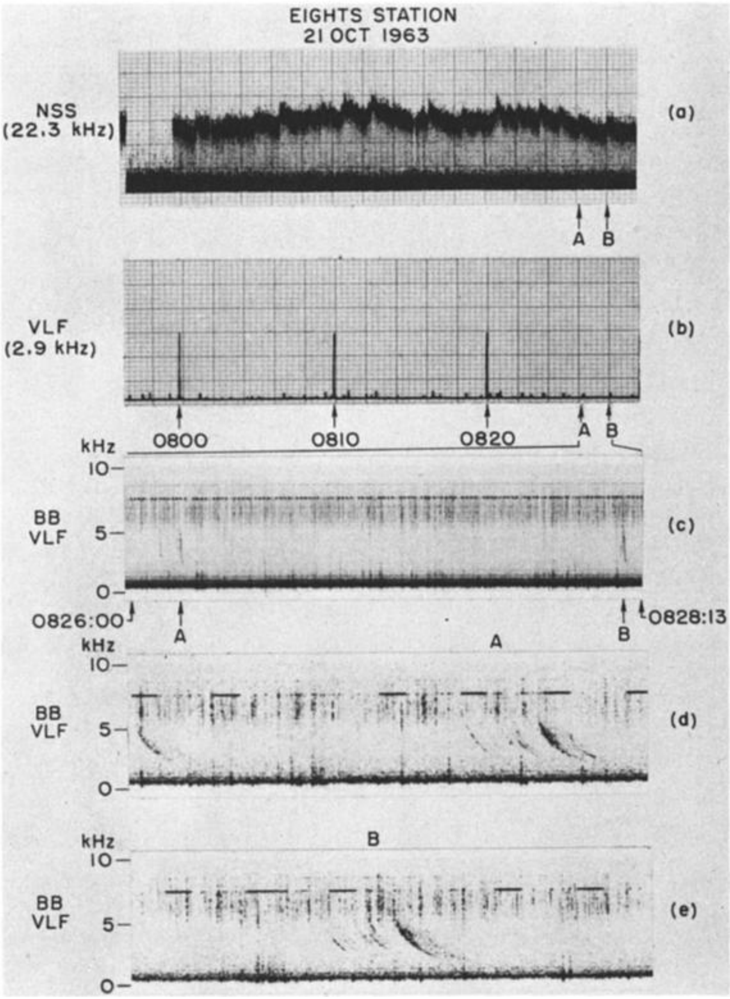

Fig. 5. (*a*) Amplitude enhancements on NSS (22.3 kHz, N-S loop). (*b*) Whistler pips on 2.9 kHz; the large spikes at 10-min intervals are timing pulses. Spectra of whistlers *A* and *B* are shown in *c* and in expanded form in *d* and *e*. The pulses appearing at 1-sec intervals at 7.55 kHz on panels *d* and *e* are frequency-translated timing signals from Station NBA on 18.0 kHz. The leading edge of the pulse coincides with the second. Timing pulses were transmitted every second excepting the 56, 57, 58, and 59th seconds and every other second ending in 4 or 9.

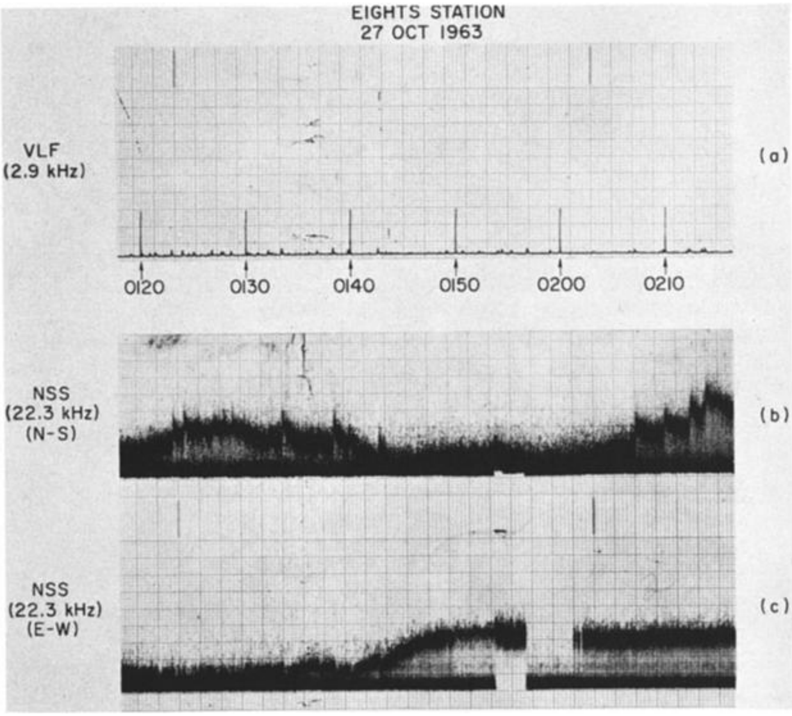

Fig. 6. (*a*) Whistler pips on 2.9 kHz; (*b*) NSS (22.3 kHz) amplitude perturbations observed on N-S loop; and (*c*) on E-W loop.

that had not yet died out. Second, many of the whistlers that are detected may come from longitudes too far removed from the great circle path between transmitter and receiver to cause an observable perturbation.

Propagation perturbations of the type just described have also been found on the paths from NSS (Annapolis, Maryland) and NPG (Jim Creek, Washington) to Quebec City (Quebec, Canada). (Details of these observations will be reported later.) Paths confined entirely to the southern hemisphere have yet to be examined.

As stated earlier, perturbations have been observed only at night, thus suggesting that the effect is swamped by the normal daytime ionization in the *D* region. An example of the diurnal variation is shown in Figure 8. The data are confined to nighttime hours along the path. Not surprisingly, the shape of the curve is suggestive of whistler rate curves for mid-latitude stations [*Helliwell*, 1965], with their predawn maximums. It is possible, therefore, that the absence of perturbations in the daytime could be partly attributed to a reduced whistler rate. Another more likely explanation is that the normal level of ionization in the daytime *D* region is sufficiently high to lower the height of reflection below the height of the perturbation. Although little seasonal data have yet been examined, we have noted a tendency for the perturbations to peak near the equinoxes, both spring and fall, and to be more common in the austral winter than in the summer.

Discussion. In view of the nighttime occurrence of the observed perturbations, we suggest that the cause is ionization produced by precipitating electrons in the *D* region below about 90 km. This same mechanism has been suggested by others [*Potemra and Zmuda*, 1970; *Doherty*, 1971] to explain VLF and LF disturbances of much longer duration. We further assume that the dumping of these electrons is caused by enhanced cyclotron resonance interaction with whistlers, either ducted or nonducted, close to the equatorial plane. Because the observed whistlers are ducted, we shall re-

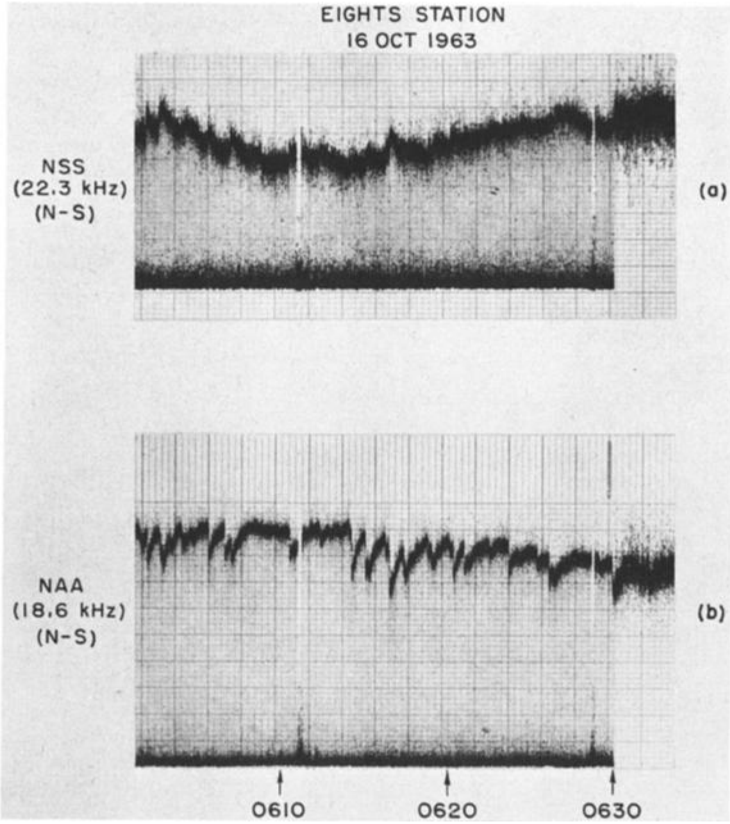

Fig. 7. Amplitude perturbations observed on (*a*) NSS (22.3 kHz) and (*b*) NAA (18.6 kHz), both on a N-S loop.

strict our discussion to this example. However, it is known from satellite observations that nonducted whistlers are common within the plasmasphere [*Smith and Angerami*, 1968]. This possibility is further supported by the fact that the perturbations are observed simultaneously at Eights and Byrd, for which the great circle paths to NSS are not coincident (see Figure 1). It is likely, therefore, that nonducted whistler energy is also involved in the precipitation process.

The resonance relations are well known [e.g., *Rosenberg et al.*, 1971] and for parallel propagation are given by

TABLE 1. Amplitude Enhancements on NSS, 22.3 kHz, North-South Loop

Date, 1963	Time Period	Number of Events	Average Rise Time, sec	Average Half-Life, sec	Average Enhancement Factor
Oct. 16	0530–0812 UT (0030–0312 LT)	33	1.9	25	1.10 (0.84 db)
Oct. 17	0608–0848 UT (0108–0348 LT)	25	2.0	33	1.41 (3.0 db)
Oct. 27	0014–0259 UT	20	2.6	33	1.38 (2.8 db)
Totals		78	2.1	30	1.27 (2.7 db)

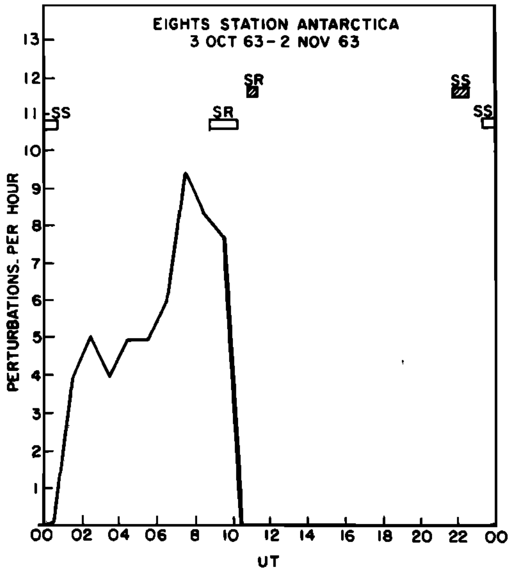

Fig. 8. Diurnal variation of rate of occurrence of NSS amplitude enhancements. Times of sunrise (*SR*) and sunset (*SS*) for $L = 2.5$ are shown by shaded bars for the northern end and by open bars for the southern end.

$$\Omega' = \omega + kv_{\parallel} \quad (1)$$

$$k = \frac{\omega}{c}\left[1 + \frac{{\omega_N}^2}{\omega(\Omega - \omega)}\right]^{1/2} \quad (2)$$

$$\Omega' = \Omega[1 - (v/c)^2]^{1/2} \quad (3)$$

where

- ω, angular wave frequency
- Ω', angular gyrofrequency of resonant electron corrected for relativistic mass change
- Ω, angular gyrofrequency of the nonrelativistic electrons comprising the background plasma
- ω_N, angular plasma frequency
- k, wave number
- $v_{\parallel}$, parallel velocity of resonant electron
- v, total velocity of resonant electron
- c, velocity of light

To obtain the relation between electron energy and whistler frequency, we must know the path latitude (to obtain Ω) and electron density (to obtain ω_N). The whistlers associated with the perturbations show travel times that are typical of midlatitude quiet time conditions. To obtain representative numbers we shall use the strongest trace from Figure 2 ($L = 2.5$; $N_e = 1800$/cc) and a diffusive equilibrium model of the magnetosphere [*Angerami and Carpenter*, 1966]. Then, with the aid of (1), (2), and (3), the relation between electron energy and whistler frequency can be computed. Curves of electron energy between 15 and 300 kev versus whistler frequency are shown in Figure 9 for these conditions. It is seen that the energies of resonant electrons that reach the *D* region (~70 to 90 km) correspond closely with the main part of the whistler spectrum (1–7 kHz).

We have not yet shown directly that the flux of electrons dumped by the whistler is sufficient to cause the observed VLF perturbations. However, this hypothesis is consistent with the X ray emission association already reported from $L = 4$ [*Rosenberg et al.*, 1971]. In that experiment, whistler-triggered VLF rising emissions of comparable apparent magnitude and duration to the whistlers of the present experiment produced bursts of X rays ($E > 30$ kev) whose count rates were several times the cosmic ray background level. The period of emission activity was accompanied by 30-MHz riometer absorption and VLF phase and amplitude perturbations over many paths [*Potemra and Rosenberg*, 1973]. It is known from satellite experiments that the fluxes of precipitated electrons (>40 kev) tend to be only a little lower

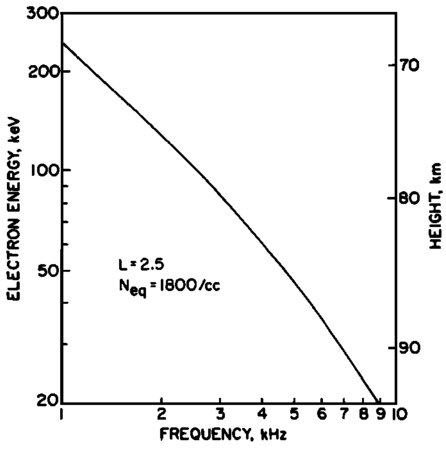

Fig. 9. Relation between electron energy and whistler frequency for $L = 2.5$ and $N = 1800$ el/cc. The right scale shows the approximate height of penetration of the energetic electrons whose energies are given by the left scale.

at $L = 2.5$ than at $L = 4$ [*Potemra and Zmuda*, 1970]. Thus it seems reasonable to conclude that the whistlers we observed at $L = 2.5$ are the most likely cause of the observed amplitude anomalies.

According to our postulated mechanism, whistler-mode signals other than those generated directly by lightning could cause short-period perturbations in VLF propagation. These include whistler-triggered emissions, artificially stimulated emissions, and spontaneous emissions. For artificially stimulated emissions, however, the phenomenon has been observed most commonly at frequencies near one-half the minimum gyrofrequency (normalized frequency equals 0.5). For the whistlers reported here, the normalized frequency is nearer to 0.1. In the X ray emission association [*Rosenberg et al.*, 1971] the normalized frequency is about 0.2. Thus the frequencies appropriate for artificially precipitating electrons into the *D* region may be considerably lower than the optimum frequency for stimulating emissions.

Our observations suggest that whistlers themselves can significantly affect the nighttime ionosphere at middle latitudes ($L \approx 2.5$). This relation provides a new mechanism to help explain temporal variations in VLF propagation. For example, it may be possible to use this mechanism to interpret fluctuations in nighttime VLF signal amplitude anomalies associated with magnetic bays [*Carpenter et al.*, 1966]. It should be possible to use whistlers as tools to study the transient response of the *D* region to the impulsive production of ionization by energetic electrons.

Controlled production of *D* region ionization may now be possible by means of man-made signals from high-power VLF transmitters (such as the transmitter currently located at Siple Station, Antarctica). With control of frequency, it should be possible to more precisely determine the particle energies than in the case of whistlers. We may then be able to locate the altitude at which the ionization is produced, thereby aiding in the study of *D* region production and loss mechanisms. Other possible experiments based on controlled particle precipitation include (1) creation of an artificial aurora, and (2) stimulation of micropulsations through modulation of the conductivity of *E* and *D* regions [*Bell*, 1972]. With suitable man-made control, it might even be possible to usefully alter the characteristics of VLF wave guide propagation.

Extensions of this experiment are needed to show what portions of the VLF propagation path are affected during an amplitude anomaly. Information on the regions of precipitation could be obtained from data on the propagation of VLF signals over different paths. Useful measurements include amplitude, phase, polarization, and direction of arrival. Direct information on the incident flux of ionizing particles could be obtained from riometers and from balloon- and satellite-borne particle detectors. In addition, VLF receivers on satellites are needed to detect the presence of nonducted whistler mode signals.

The interpretation of the recovery times (30 sec), in terms of ionization production and loss rates in the *D* region, will be an important step in further understanding the complex behavior of the lower ionosphere. It is also necessary to develop expressions for pitch angle scattering by coherent waves because available scattering theory is limited to broad-band noise.

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