VOL. 80, NO. 1 JOURNAL OF GEOPHYSICAL RESEARCH JANUARY 1, 1975

Fast Hisslers in Substorms

J. C. Siren[1]

Radioscience Laboratory, Stanford University, Stanford, California 94305

'Fast hisslers,' or very brief bursts of auroral hiss dispersed in the whistler mode, have been found to occur in substorms at Byrd station, Antarctica. Broad band VLF data recorded on tape during breakup phases of substorms were monitored aurally. In two of 19 substorm breakup phases observed at Byrd station, fast hisslers were heard. The data were subsequently spectrum analyzed to permit measurement of whistler mode dispersion, from which the altitudes of their origin were estimated. Some of the fast hisslers exhibited a 'nose' or nonextremal frequency of earliest arrival. This feature permitted an estimate of altitude of origin that is nearly independent of the field line electron density distribution model. Altitudes of origin of 1800–30,000 km are deduced. Some fast hisslers have been observed at phases other than the breakup phase. Fast Fourier transform spectra show that fast hisslers are indistinguishable from dispersed short pulses of band-limited white noise. Incoherent Cerenkov radiation from precipitating auroral electrons is of insufficient intensity to account for this phenomenon.

'Fast hisslers' are very brief bursts of auroral hiss. Their brevity makes measurable the whistler mode dispersion of the bursts that results from propagation through the magnetosphere. They were first observed during a substorm at Byrd station, Antarctica (80°S, 120°W) at −72° geomagnetic latitude [*Siren,* 1972]. We have sought to determine the frequency of occurrence of these phenomena by examining broad band VLF data tape recorded at Byrd station. Our data base is a sequence of broad band VLF tape recordings made during a high duty cycle continuous recording campaign in 1967 covering the interval 0005 UT on June 16 to 2000 UT on July 17. The 0- to 20-kHz signal received with the 32-km horizontal dipole antenna was received for 42 min of each hour of this interval. Tape changes were made during off intervals, when it was possible. The average duty cycle over the interval was 66%.

DATA SELECTION

The data set examined in this work was selected through the requirement that the geophysical conditions prevailing during the recordings selected resemble those prevailing at 0439 UT on August 14, 1967, when the phenomenon occurred. A substorm had then been in progress. (In what follows we apply criteria based on *Morozumi*'s [1965] and *Morozumi and Helliwell*'s [1966] studies of Byrd station substorm phases. What they called an 'N-2' phase is now generally called the 'breakup' or 'expansion' phase. *Brice* [1968] interpreted the N-2 as the passing of the 'auroral bulge' over the location of the observer.) During the 5-min breakup phase, which began at 0437 UT, there occurred an increase in 558-mμ auroral intensity, a 380-γ negative bay in the magnetometer H component, a 1.45-dB absorption bay at 30 MHz, a 23-dB increase in (N-S component) micropulsation intensity, and increases of 8 dB or more in VLF hiss intensity relative to background noise in the 2- to 4-kHz, 11- to 13-kHz, and 31- to 38-kHz bands, respectively. A westward-traveling surge in the aurora, as identified in Byrd station all-sky camera photographs, appeared at 0439 UT and passed the zenith at 0441 UT. The criteria met by the substorm events we selected for examination are given below. We deemed adequate for examination all events meeting any five of the seven simultaneous criteria characterizing an N-2 phase.

1. 30-MHz relative ionospheric opacity: ≥0.50-dB increase.
2. Magnetometer H component: ≥30-γ negative bay.
3. 558-mμ auroral intensity: increase.
4. Micropulsation N-S component: ≥6-dB increase.
5. 31- to 38-kHz VLF hiss intensity: ≥10-dB increase above background.
6. 11- to 13-kHz VLF hiss intensity: ≥6-dB increase above background.
7. 2- to 4-kHz VLF hiss intensity: ≥6-dB increase above background.

We have specified somewhat different criteria from those specified by Morozumi and Helliwell to identify phases that are like the N-2. We did not record ELF (2–40 Hz) data, so the presence of ELF bursts was not a criterion. Our 558-mμ data came from a coruscatometer (sensitive to variations in auroral light intensity) viewing a cone of 4° half angle about the zenith, whereas Morozumi and Helliwell's data came from an all-sky photometer. Other differences existed. Nevertheless, the events selected are as distinctive as Morozumi and Helliwell's N-2 phases. In our opinion the number of events from this interval that they would have designated N-2 that we did not select, and vice versa, is a small fraction of the 24 selected. We required in addition that the event commence during a recorder on period. This requirement eliminated five events. Table 1 lists the remaining 19 events. The times of these events are indicated in Figure 1 by a vertical solid line, corresponding to the time of commencement in universal time. The dashed lines correspond to the event on August 14, 1967 (Figure 1*c*), and to a fast hissler occurrence on September 18, 1971 (Figure 1*d*), to be discussed below. The extended lines are those events in which fast hisslers occurred. Auroral midnight is the time when the antisolar point is on the great circle through Byrd station and the center of the southern auroral zone. Morozumi and Helliwell had found N-2 phases clustered within a few hours of auroral midnight. We found that 18 of 19 events occurred within 6 hours of auroral midnight.

DATA ANALYSIS

The selected tape-recorded VLF data were aurally monitored at the tape speed (19 cm/s) at which they had been

---

[1] Now at Department of Applied Physics and Information Science, University of California at San Diego, La Jolla, California 92037.

TABLE 1. Substorm N-2 Phase Events

Date	Time, UT	30-MHz Relative Ionospheric Opacity Increase, dB	Magnetometer *H* Component Bay, γ	558-mμ Auroral Intensity	Micropulsation N-S Component Increase, dB	VLF Hiss Intensity Increase 31- to 38-kHz Band, dB	 11- to 13-kHz Band, dB	 2- to 4-kHz Band, dB
			N-2 Events Examined in This Paper					
June 18, 1967	0356	0.13	no data	increase	10	14	11	8
June 18, 1967	0519	1.69	no data	increase	20	18	16	15
June 21, 1967	0318	0.23	0	increase	29	24	16	14
June 21, 1967	0402	0.35	-20	increase	14	12	15	12
June 22, 1967	0416	0.11	-60	increase	18	18	12	10
June 24, 1967(*a*)	0554*	1.08	-280	increase	18	12	6	10
June 27, 1967	0015	2.22	-260	increase	>20	>20	>18	17
June 27, 1967	0523	5.25	-480	increase	20	20	8	0
June 30, 1967	1818	2.36	-30	increase	20	0	0	10
July 3, 1967	0247	0.60	-30	increase	19	20	>18	19
July 3, 1967	0318	0.74	-110	increase	>14	20	15	20
July 4, 1967	0429	0.94	-200	increase	12	20	10	5
July 6, 1967(*b*)	2226*	1.48	-80	no data	2	30	10	16
July 6, 1967	2248	2.09	-40	no data	9	32	>17	20
July 7, 1967	0225	2.15	-230	no data	8	23	18	19
July 7, 1967	0300	1.07	-120	no data	6	10	13	16
July 11, 1967	0052	0.50	-240	increase	8	16	5	0
July 13, 1967	0454	2.58	-90	increase	23	16	18	>22
July 14, 1967	0329	0.62	-80	increase	>15	14	>19	>19
			Other N-2 Events					
Aug. 14, 1967(*c*)	0439*	1.45	-380	increase	23	14	8	8
Sept. 18, 1971(*d*)	0135*	no data	-320	no data	decrease	16	13	23

The letters in parens following the date correspond to the events shown in Figures 1 and 2.
*Fast hisslers observed.

recorded. This procedure was followed because hisslers heard through earphones sound different from whistlers and can be distinguished from whistlers by their sound more readily than by their visual appearance on Rayspan spectrum analyzer records. This difference is probably because all signal phase information is suppressed by the sprectum analyzer. Hisslers are clearly hisslike in comparison with the somewhat musical sound of whistlers, even multicomponent or 'swishy' whistlers.

The aural monitoring included an interval from 10 min before to 10 min after each N-2 phase commencement. Fast hisslers were heard in two of the recordings, at 0554 UT on June 24, 1967, and at 2226 UT on July 6, 1967. These data were then analyzed by a Rayspan spectrum analyzer, so that dispersion measurements could be made. Rayspan spectra of these fast hisslers are shown in Figures 2*a* and 2*b*, respectively. We include, for comparison, fast hissler spectra from the event on August 14, 1967 (Figure 2*c*), and the occurrence on September 18, 1971 (Figure 2*d*). Although the June 24 and July 6 fast hisslers were more intense than those observed on August 14, the background noise (consisting of steady and impulsive hiss) was relatively even more intense; as a result, the fast hisslers were less sharply defined. The fast hisslers did not occur in intervals longer than 1 min nor more often than in one such interval per substorm.

Figure 3 indicates the predicted trajectories in frequency-time space of fast hisslers. The curves are parametric in altitude of origin. Altitude of origin of the observed fast hisslers was estimated by comparison with these theoretical spectra that are based on the following assumptions: the fast hisslers originated at point sources on the field line passing through Byrd station and were undispersed at the points of origin; propagation was 'longitudinal' (wave normal was parallel to the local magnetic field); and the electron plasma frequency and gyrofrequency along the field line were the same as those used by ***Lim and Laaspere*** [1972] in their Cerenkov radiation calculations. Note that as altitude of origin increases, time delay increases at all frequencies, dispersion increases monotonically at the lower frequencies, and a 'nose' or nonextremal frequency of earliest arrival appears and decreases rapidly with altitude. Dashed portions of the curves indicate nonducted whistler mode propagation along the higher-altitude portion of the ray path.

For a given altitude of origin the nose frequency of a fast hissler is a relatively less rapidly varying function of plasma frequency along the path of propagation than is the propagation delay at the nose frequency. Under the assumption that the plasma frequency along the field line is that given by the Lim and Laaspere model, the nose frequency of a fast hissler

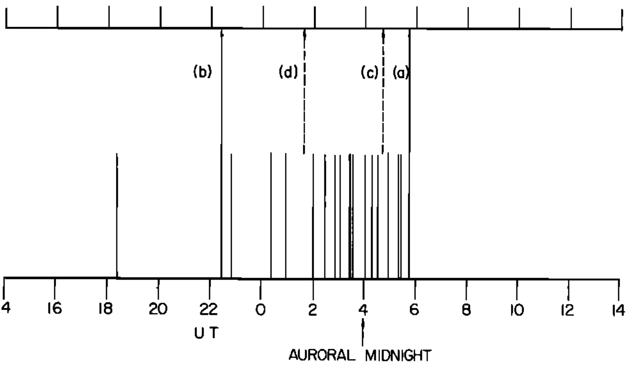

Fig. 1. Time distribution of substorm N-2 phases: (*a*) 0554 UT on June 24, 1967, (*b*) 2226 UT on July 6, 1967, (*c*) 0439 UT on August 14, 1967, and (*d*) 0135 UT on September 18, 1971. The extended lines are those events in which fast hisslers occurred.

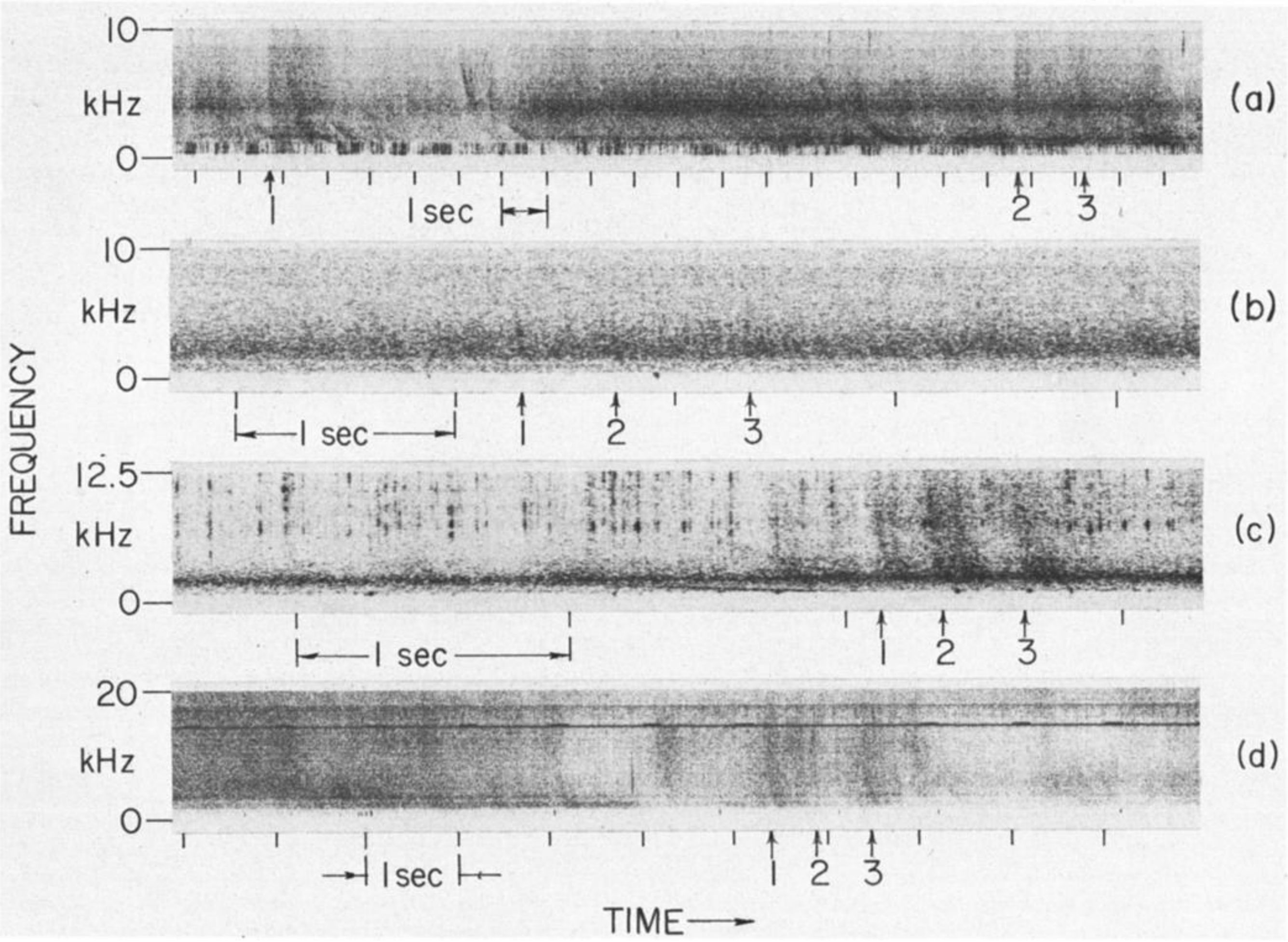

Fig. 2. Frequency-time spectra of fast hisslers. The numbered tick marks beneath each spectrum denote fast hisslers. Letters in parentheses refer to events labeled in Figure 1.

originating at 25,600 km is 8.5 kHz, and the source to ground propagation time at the nose is 0.23 s. Increasing the plasma frequency by a factor of 1.4 (the consequence of doubling the electron density) everywhere along the field line would raise the nose frequency by only 0.1 kHz, or about 1%, but it would increase the source to ground propagation time at the nose by 0.08 s or 37%. Figure 4 shows nose frequency as a function of altitude for the assumed model. In view of these results we have based our altitude estimates on nose frequency, when that has been observable, or on dispersion, otherwise. Under these assumptions the fast hisslers labeled 1, 2, and 3 in Figure 2*b* originated at 9400, 3900, and 1800 km. These are the least dispersed hisslers we have observed. The spectral intensity of hissler 1 was 9.7×10^{-16} W m^{-2} Hz^{-1} in the frequency band 2–4 kHz. The hissler labeled 3 in the June 24 event (Figure 2*a*) showed no evidence of a nose up to its highest observed frequency, 9 kHz. This finding indicated an altitude of origin not greater than 25,000 km. However, the dispersion at the lower frequencies is greater than the dispersion that can result from propagation along an auroral zone field line from an altitude with the plasma frequency model assumed. We find that both high- and low-frequency portions of this hissler can be accounted for with a model in which the plasma frequency at each point along the field line is double that of the Lim and Laaspere model. With this assumption the altitude of origin is estimated as 21,000 km. The hisslers labeled 1 and 2 in Figure 2*a* exhibited noses at 5 and 6.5 kHz, respectively. Their altitudes of origin are estimated as 30,000 and 28,000 km. The peak spectral intensity of the most intense fast hissler of this event, the one labeled 2, was 7.5×10^{-17} W m^{-2} Hz^{-1} in the frequency band 2–4 kHz and 1.3×10^{-16} W m^{-2} Hz^{-1} in the frequency band 11–13 kHz.

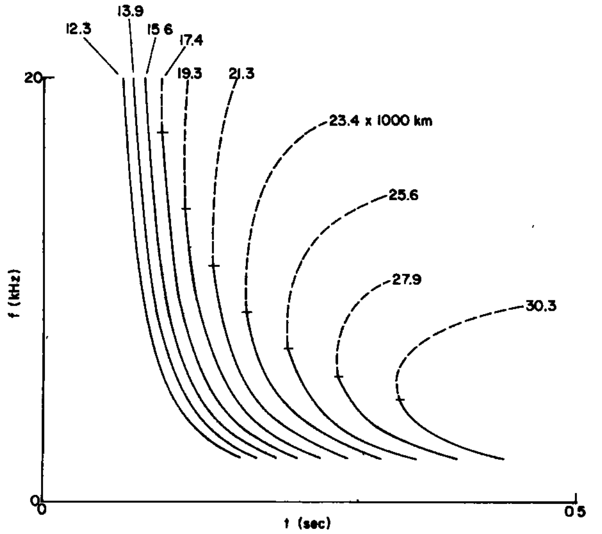

Fig. 3. Theoretical trajectories in frequency-time space of fast hisslers. Dashed portions of the curves indicate nonducted whistler mode propagation along the higher-altitude portion of the ray path.

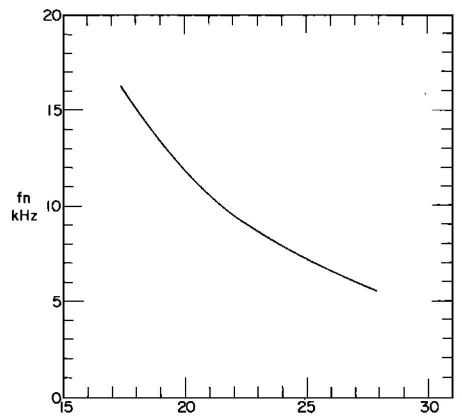

Fig. 4. 'Nose frequency,' or nonextremal frequency of earliest arrival of fast hisslers as a function of altitude of origin.

Spectra of nose hisslers extending up to the highest frequency yet observed, 18 kHz, are given in Figure 2*d*. The observed nose frequency, 8.5 kHz, corresponds to an altitude of origin of 25,600 km. We were able to measure peak spectral intensity in three bands: 1-2 kHz, 2-4 kHz, and 11-13 kHz. The spectral intensities were, respectively, 3×10^{-17}, 1×10^{-16}, and 4×10^{-16} W m^{-2} Hz^{-1}. This event occurred during a night of substorm activity, but an N-2 phase was not in progress at Byrd station at this time. These hisslers were noted first by visual inspection of the data.

Conventional fixed frequency fast Fourier transform (FFT) spectra have been made of the fast hisslers in the August 14 event [*Siren*, 1972]. The FFT permits the maximum possible frequency and time resolution consistent with the theoretical limitation $\Delta f \cdot \Delta t \gtrsim 1$. The amplitude spectra from that event were found to be indistinguishable from those expected for dispersed pulses of Gaussian noise.

DISCUSSION

Peak spectral intensities observed in these VLF emissions range from 3×10^{-17} to nearly 10^{-15} W m^{-2} Hz^{-1}, almost 2 orders of magnitude greater than in the fast hisslers of the August 14 event. *Taylor* [1973] and *Taylor and Shawhan* [1974] calculated the volume of the region of space from which the August 14 emissions would have been radiated, assuming Cerenkov radiation from precipitating auroral electrons was the source. They found the volume is that of a cube several thousand kilometers on a side if the source region altitude is 15,000 km. They assumed, however, that the source region had a cross section some 750 × 750 km in the plane perpendicular to the local magnetic field. The source region would therefore have to extend along the field line for a distance many times the several thousand kilometers calculated as the cube size in order that the source region have sufficient volume. The source region required to produce the hisslers described in this paper would have an even larger volume, in proportion to the ratio of intensities. Taylor found also that Cerenkov radiation at these frequencies would have to propagate with wave normal directions greater than 89° away from the local magnetic field direction in the magnetosphere, whereas wave normal directions less than 12° away from the local magnetic field direction are necessary for penetration through the ionosphere. Waves with greater wave normal angles are totally reflected at the lower ionosphere boundary. On the basis of these considerations, we find incoherent Cerenkov radiation insufficient to account for the fast hisslers.

We wish to examine further our assumption that the sources were on the Byrd station magnetic field line in the magnetosphere. The VLF viewing area of Byrd station extends in latitude from about $L = 3.5$ to about $L = 9$ [*Carpenter*, 1966]. Our assumption is that the sources were on the field line through the center of this viewing area. If the sources had been instead on field lines as far away as the fringes of this area, their calculated altitudes would not have been significantly different. The sources would still have been on the side of the equatorial plane nearer the receiving site. Whether the fast hisslers originated on open or closed field lines is a different matter. It is possible that at least some of the fast hisslers originated on open field lines. Two of the events (August 14 and June 24) were preceded by intervals of about 80 min or more of continuous southward interplanetary magnetic field as measured by Explorer 33 (D. Colburn, personal communication, 1973). This situation is sufficient to have caused the auroral oval to have expanded equatorward of Byrd station by the time of the substorms if the behavior of the southern auroral oval is like that of the northern oval [*Akasofu et al.*, 1973]. The fast hissler sources might then have been on polar cap (open) field lines. The significance of this possibility is that parallel electric fields are more likely to occur on open than on closed magnetic field lines. Field-aligned currents are driven by parallel electric fields. A state of current saturation is necessary for the establishment of potential double layers [*Block*, 1972], which we propose as a mechanism for accelerating auroral electrons to high energies in quite small distances and which may be near or coincide with the fast hissler sources. However, double layer theory does not predict whether magnetospheric double layers, should they exist, can be established in times as short as the rise times of fast hisslers (20-80 ms).

None of the fast hisslers we have observed is morphologically inconsistent with the assumption that hisslers originate as undispersed pure noise pulses at fixed points on auroral zone field lines. This is the conceptually simplest assumption consistent with the data. We have calculated the spectra predicted from moving sources but have been unable to account as well for the observed morphology by the assumption of sources moving with constant velocity. The possibility remains that the sources are moving but only emit radiation for a short time when conditions for partial or total wave coherency exist. This explanation would account for the impulsive character of the radiation.

Acknowledgments. I acknowledge many stimulating discussions with Robert A. Helliwell and Donald L. Carpenter, whose advice is gratefully received. This research was supported in part by the National Science Foundation, Office of Atmospheric Sciences, under grant GA-32590X and in part by the National Science Foundation, Office of Polar Programs, under grant GV-28840X.

The Editor thanks R. L. Dowden and another referee for their assistance in evaluating this paper.

REFERENCES

Akasofu, S.-I., P. D. Perreault, F. Yasuhara, and C.-I. Meng, Auroral substorms and the interplanetary magnetic field, *J. Geophys. Res.*, *78*, 7490, 1973.

Block, L. P., Potential double layers in the ionosphere, *Cosmic Electrodynamics*, *3*, 349, 1972.

Brice, N., Magnetospheric and high latitude ionospheric disturbance phenomena, in *Physics of the Magnetosphere*, edited by R. L.

Carovillano, J. F. McClay, and H. Radoski, pp. 563–585, D. Reidel, Dordrecht, Netherlands, 1968.

Carpenter, D. L., Whistler studies of the plasmapause in the magnetosphere, 1, Temporal variations in the position of the knee and some evidence on plasma motions near the knee, *J. Geophys. Res.*, *71*, 693, 1966.

Lim, T. L., and T. Laaspere, An evaluation of the intensity of Cerenkov radiation from auroral electrons with energies down to 100 eV, *J. Geophys. Res.*, *77*, 4145, 1972.

Morozumi, H., Diurnal variation of aurora zone geophysical disturbances, *Rep. Ionos. Space Res. Jap.*, *19*, 1, 1965.

Morozumi, H. M., and R. A. Helliwell, A correlation study of the diurnal variation of upper atmospheric phenomena in the southern auroral zone, *Sci. Rep. 2, SU-SEL-66-124*, pp. 16–21, Stanford Elec. Lab., Stanford Univ., Stanford, Calif., 1966.

Siren, J. C., Dispersive auroral hiss, *Nature Phys. Sci.*, *238*, 118, 1972.

Taylor, W. W. L., Generation and propagation of electromagnetic waves in the magnetosphere, Ph.D. thesis, Dep. of Phys. and Astron., Univ. of Iowa, Iowa City, 1973.

Taylor, W. W. L., and S. D. Shawhan, A test of incoherent Cerenkov radiation for VLF hiss and other magnetospheric emissions, *J. Geophys. Res.*, *79*, 105, 1974.

(Received December 21, 1973;
accepted September 25, 1974.)