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Midlatitude Observations of Nighttime VLF Signal-Amplitude Anomalies Associated with Magnetic Bays

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Introduction. The purpose of this letter is to report the observation of VLF propagation anomalies occurring on midlatitude paths during local nighttime. The anomalies appear significant because they are not accompanied by the usual sources of perturbation—solar flares, high-altitude nuclear detonations, or severe magnetic storms. The nighttime occurrence of the anomalies effectively eliminates solar-flare-produced SID's, which are almost exclusively a dayside phenomenon. The changes do, however, resemble those produced during daytime by solar flares [*Budden and Ratcliffe,* 1937; *Bracewell and Straker,* 1949; *Westfall,* 1961; *Mitra,* 1964]. On rare occasions solar flares produce disturbed conditions on the nightside (see review of February 23, 1956, event by *Ortner et al.* [1960]), but there are no reports of flare activity at the times under consideration. The character of the anomalies is not unlike that produced by trapped electrons from distant high-altitude nuclear explosions [*Zmuda et al.,* 1964; *Sechrist,* 1964]. There are, however, no reports of nuclear testing at the times under discussion. The short-term nature of the anomalies is quite different from the long-term delayed changes expected from severe magnetic storms [*Bracewell et al.,* 1951; *Burgess,* 1964], and no notable storms were reported for several days prior to the anomalies. The signal perturbations to be discussed here more closely resemble perturbations observed in the auroral zone [*Bates and Albee,* 1965; *Reder et al.,* 1964]. The midlatitude perturbations were accompanied by magnetic bays. Magnetic bays often accompany auroral-zone perturbations, but a direct correlation apparently does not exist in that region.

VLF data. The field strength of six VLF transmitters is recorded continuously at Stanford University. On October 5, 1963, at 0903 GMT (0103 local time) and on January 16, 1964, at 0937 GMT (0137 local time) large amplitude anomalies were observed on some of the signals. All the paths except one were in total darkness. A search of VLF data collected by Stanford University at Quebec City, Canada, and by Stanford Research Institute at Tracy, California, also revealed anomalies during these two days. The propagation paths considered in the discussion that follows are shown in Figure 1. Also shown in Figure 1 are the sunrise-sunset lines for 90-km altitude at the times of the disturbances (October 5, solid; January 16, dashed). (All times are GMT.)

The relative amplitude of the vertical electric field of six VLF transmissions received at Stanford University from 0800 to 1100 on October 5, 1963, is shown in Figure 2. Three of the signals, NAA, NPG, and NSS, show distinct perturbations beginning at about 0903. Rapid changes occur in the first 5 minutes and levels remain disturbed for about 90 minutes. On the basis of several days of control data, the remaining three signals in Figure 2—NPM, NDT, and NBA—followed their normal diurnal pattern during this period. Of the three signals monitored at Quebec City (see Figure 3) on October 5, only one, NAA, was definitely perturbed. The rate of decrease of NAA amplitude accelerated rapidly at 0905; by 0911 the level had decreased at least 30 db. The amplitude of NAA recovered quickly and following its normal diurnal pattern after 0918. The remaining two signals at Quebec—NBA and GBR—may have been slightly disturbed, but the de-

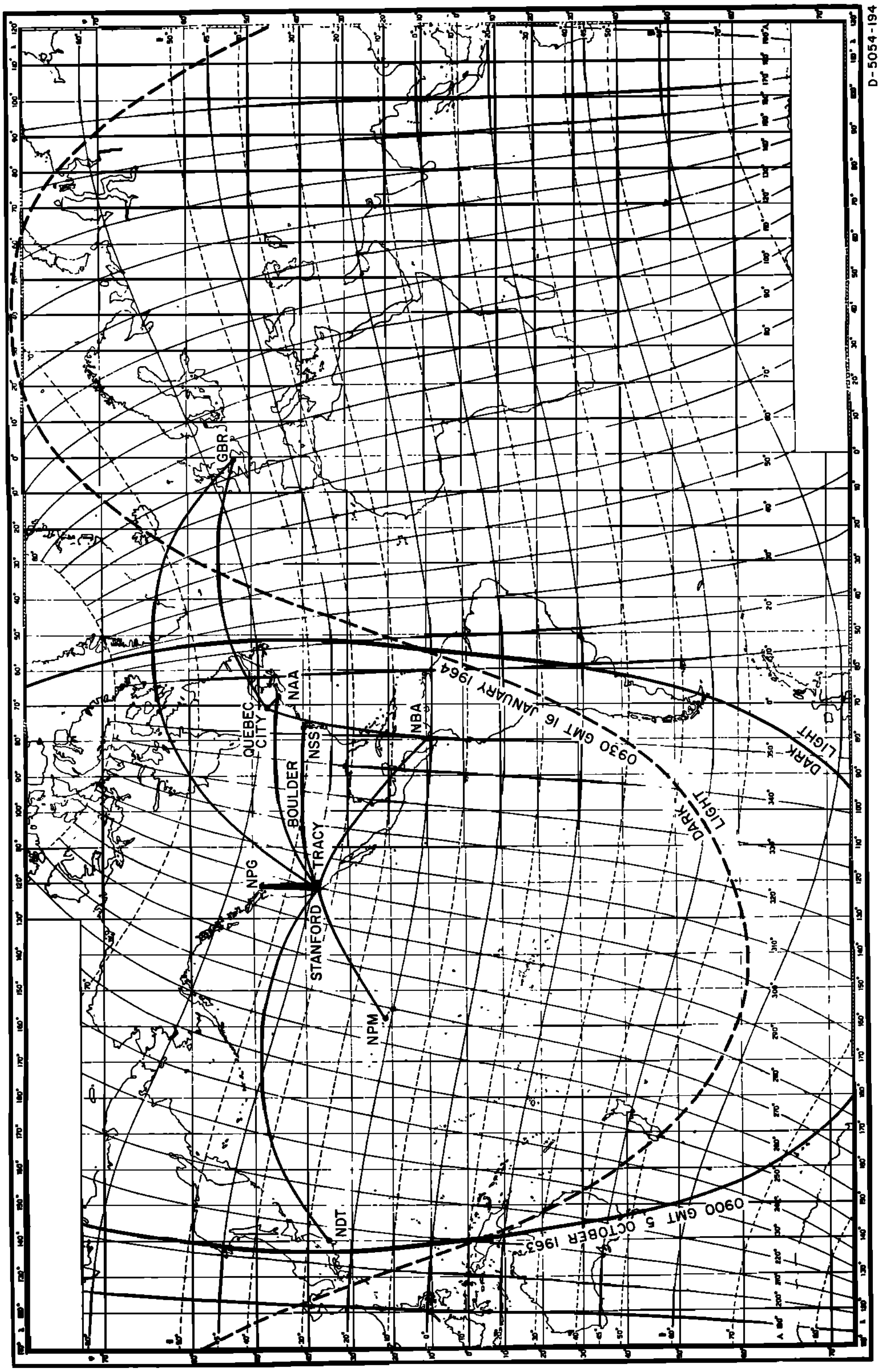

Fig. 1. Location of VLF propagation paths and appropriate sunrise-sunset lines.

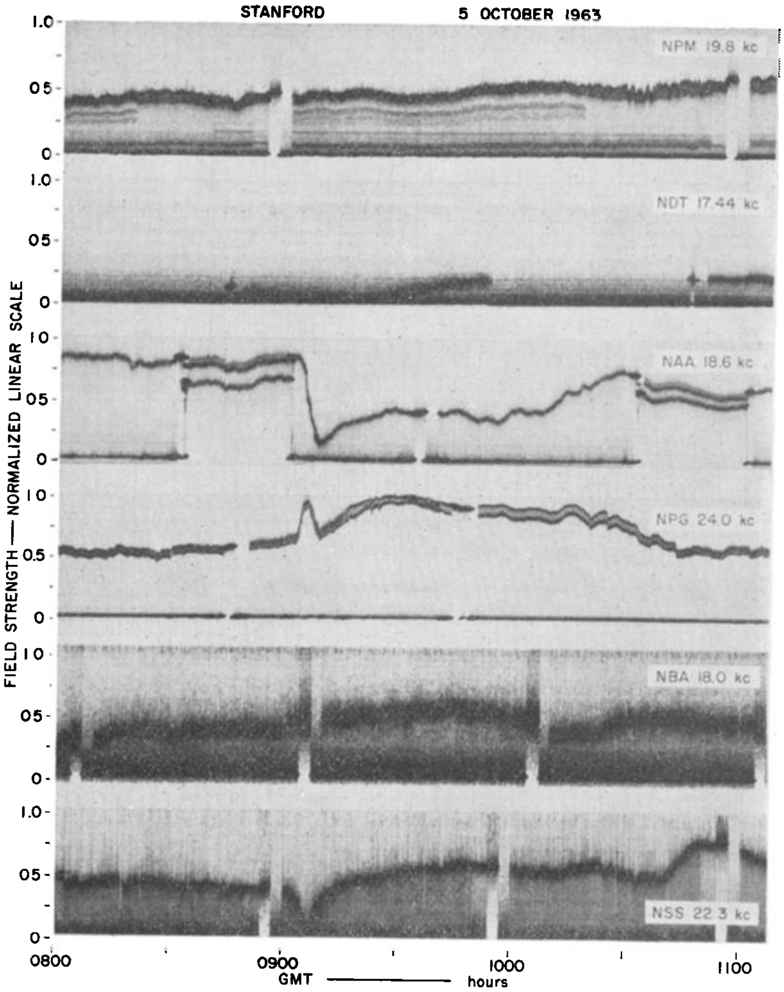

Fig. 2. Vertical electric field strength of VLF transmissions received at Stanford, California, on October 5, 1963.

viations from a normal diurnal pattern were not conclusive because of the large sunrise variation.

On January 16, 1964, of the six VLF transmissions received at Stanford from 0900 to 1200 (shown in Figure 4), only one, NPG, was definitely perturbed. The amplitude of NPG began increasing at about 0937 and was disturbed for about 90 minutes. A second perturbation of NPG signal was superimposed on the first perturbation beginning about 0958. The NAA and NSS signal levels at Stanford strongly suggest some disturbance. Although the fluctuations in the amplitude of these signals may be no larger than those on a typical night, the temporal coincidence with the NPG perturbations is suggestive of a common cause. The NPM signal level may have been slightly more unstable than usual during the disturbance, but the NDT and GBR signal levels apparently followed their normal variation then. The variation of NPG signal at Tracy, California, on January 16 was nearly identical with the nearby observations at Stanford. The second perturbation at Stanford at 0958 was apparently not present at Tracy.

The VLF anomalies described above were discussed with Dr. J. H. Crary of the National Bureau of Standards and Dr. F. H. Reder of the U. S. Army Research and Development

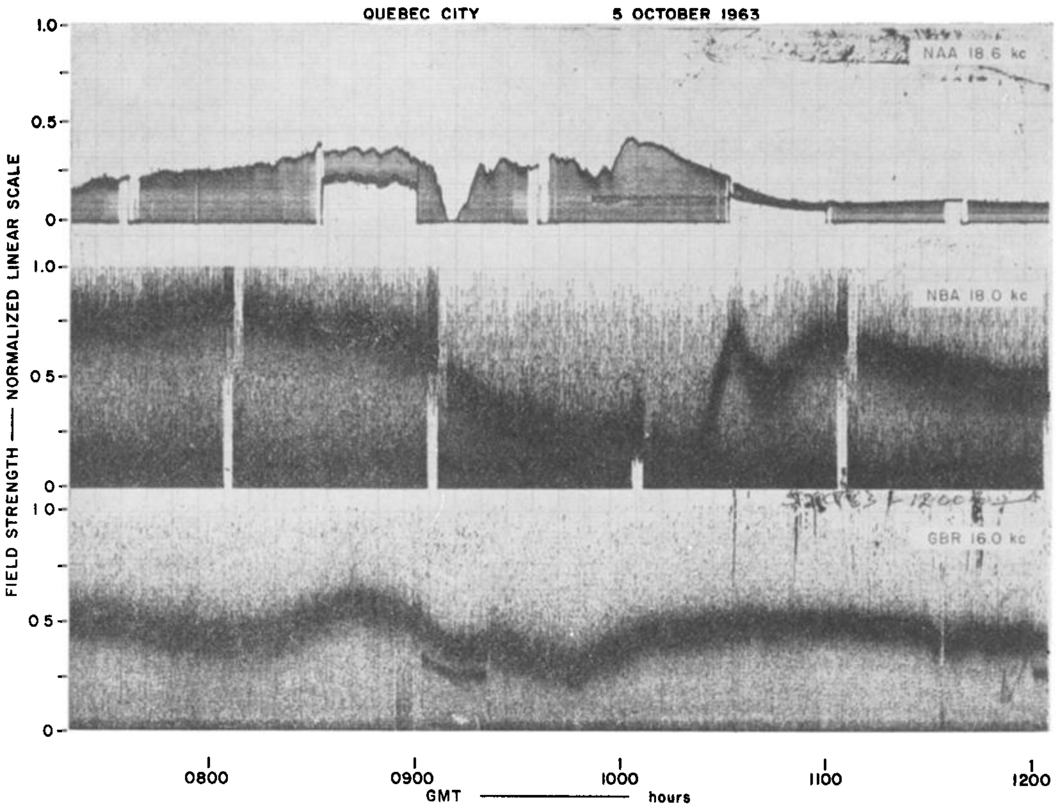

Fig. 3. Vertical electric field strength of VLF transmissions received at Quebec City, Canada, on October 5, 1963.

Laboratory. A search of the NBS VLF and LF data revealed that a number of signals received at Boulder, Colorado, were disturbed at the times under discussion. The most severe amplitude and phase perturbations occurred on the NAA, NSS (22.3 and 88.0 kc), and CYZ (80.0 kc from Ottawa) paths. Data collected by Dr. Reder at Fort Monmouth, New Jersey, and those available to him from Stockholm and Kiruna, Sweden, also revealed several disturbed paths at the times under discussion. The most significant perturbations were observed on the paths from NPM to Fort Monmouth and to Stockholm and on the paths from NPG to Fort Monmouth and to Stockholm (October 5 only).

Magnetometer data. Magnetometer records from many observatories providing worldwide coverage were examined for the two days of interest. Forty-seven stations were recording during the October 5 event, and sixty were recording during the January 16 event. Magnetic disturbances were observed at most stations, with the bays becoming smaller at the stations removed in latitude and longitude from College, Alaska, where the largest change was observed. The change in amplitude of the H component at College was about 450 γ for October 5, 1963, and 900 γ for January 16, 1964. Relatively large magnetic bays were also observed at the antarctic stations. The H component for the October 5 event is shown in Figure 5 and for the January 16 event in Figure 6. The stations reported here are College, Alaska; Sitka, Alaska; Meanook, Alberta; Tucson, Arizona; and MacQuarie Island near New Zealand. The onset time of the magnetic bay at each station is listed in Table 1. These times precede the onset of the VLF amplitude anomaly by as much as 15 minutes. The magnetic activity during the January 16 event was

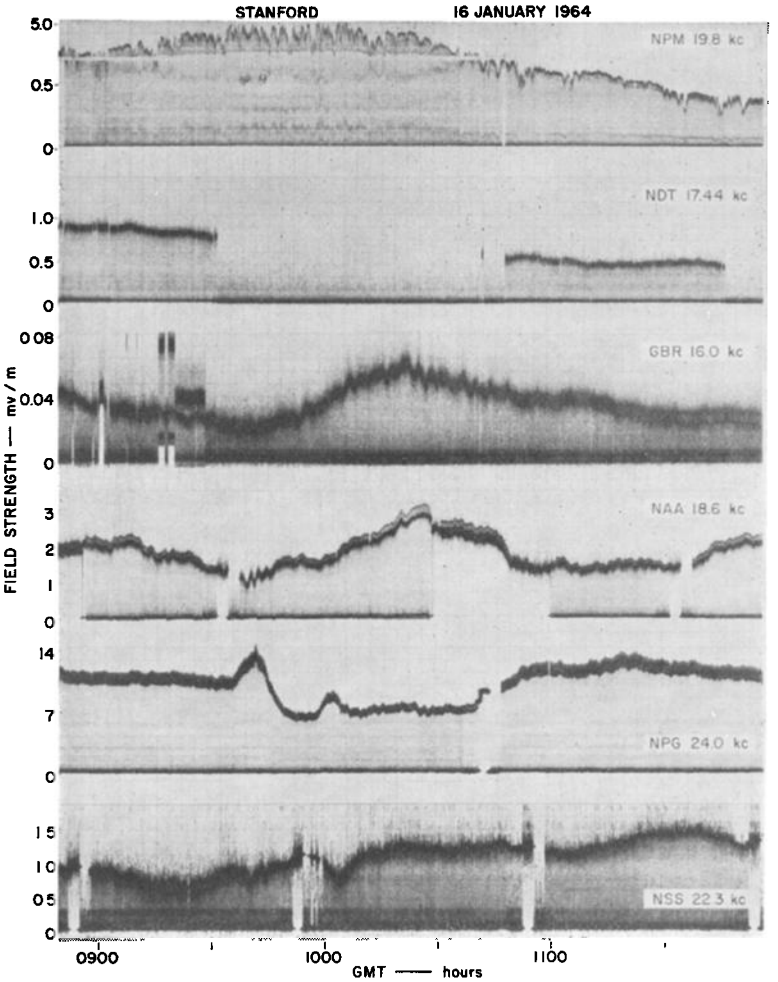

Fig. 4. Vertical electric field strength of VLF transmissions received at Stanford, California, on January 16, 1964.

higher than on October 5, as indicated in Table 2, where the K_p indices for the two days reported are listed.

Riometer data. The occurrence of magnetic bays and of disturbed VLF propagation conditions suggests that other ionospheric measurements may also have been disturbed. One ionospheric measurement uses a riometer [*Little and Leinback,* 1959] to investigate absorption in the lower ionosphere. For the two days of interest, riometer data published by the *University of Alaska* [1964*a, b*] and the *Air Force Cambridge Research Laboratory* [1964], as well as those available at Stanford Research Institute (R. S. Leonard and J. C. Hodges, personal communication) were examined. Data were also obtained from the Defence Research Board of Canada (R. Montibetti), the University of California (R. R. Brown), and the National Bureau of Standards (H. H. Sauer). Data from some twenty stations provided coverage in three general areas. The most heavily covered area was the higher-latitude region of North America from a magnetic L value of 2 to more than 200. Three stations in the Antarctic were conjugate to northern-hemisphere stations. The remaining four stations with L value near 1 effectively ringed the equator.

Riometer absorption on October 5 was observed at stations with L values from 4.2 to

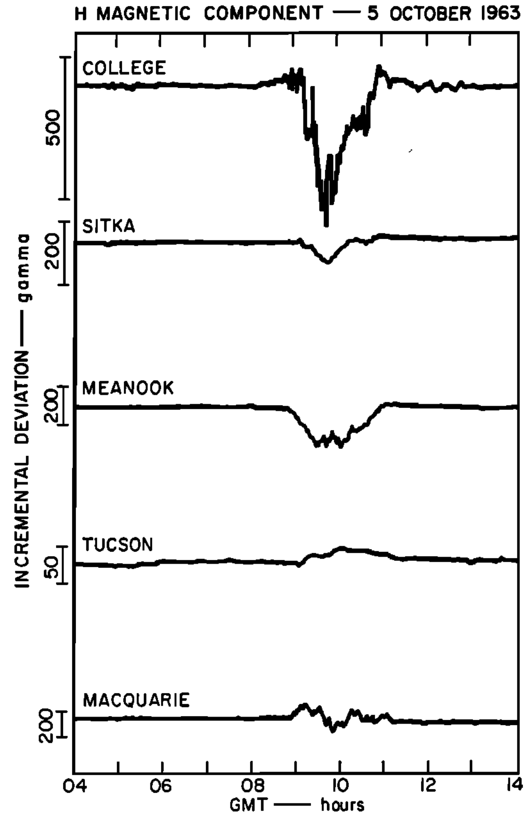

Fig. 5. Deviation of the horizontal component of the earth's magnetic field at selected sites on October 5, 1963.

8.6 and was not observed at stations with L values below 3.6 or above 14.8. Stations in the transition region—one at $L = 4.0$ and one at $L = 13.5$—observed a small absorption event of short duration beginning at about 1030, which may have been related to the earlier, more severe change at intermediate L values. At College, Alaska ($L = 5.43$), the onset was approximately 0850, about 13 minutes earlier than the VLF anomaly onset, while at nearby Kotzebue, Alaska ($L = 5.9$), the onset was approximately 0902. Some absorption persisted at the Alaskan stations until 1200. Absorption was also observed at three stations near Hudson Bay and at the conjugate of one of them—in the Antarctic. Onset at the latter stations was at about 0930, peak absorption at about 1030, and recovery at about 1200.

The riometer absorption on January 16 was apparently more severe and extended to a slightly lower magnetic latitude than the October 5 event. Absorption was observed at stations with L values of from 3.9 to 7.25 and was not observed at stations with L values below 2.8 or above 14.8. A station in the upper transition region ($L = 13.5$) may have observed a disturbance after 1020; no data were available from stations between $L = 2.8$ and $L = 3.9$. Stations at College ($L = 5.43$) and Kotzebue ($L = 5.9$), Alaska, again reported the earliest onset—0923 and 0929, respectively—about 14 minutes and 9 minutes earlier than the VLF anomalies. The Alaskan changes reached their maximum deviation at 0935 to 0940 and persisted until perhaps 1500. The degree of absorption fluctuated noticeably during the disturbance. The onset of the absorption at stations with more eastern longitude was later

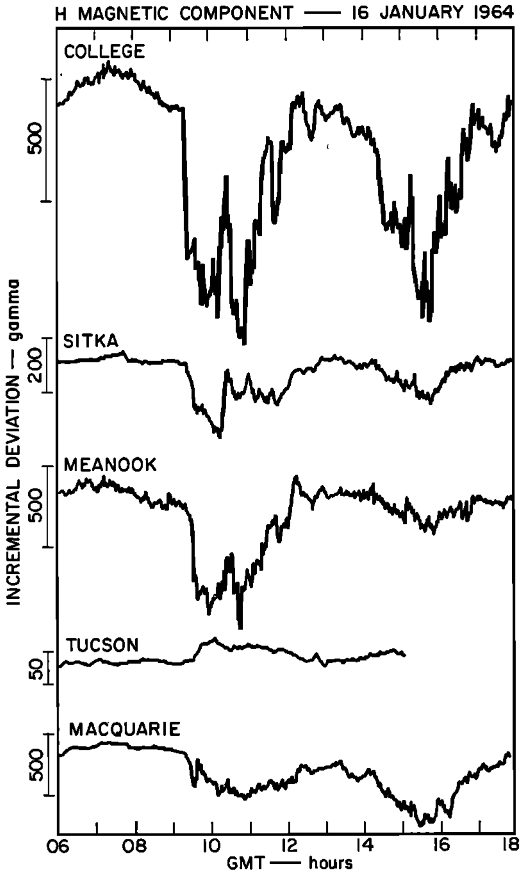

Fig. 6. Deviation of the horizontal component of the earth's magnetic field at selected sites on January 16, 1964.

TABLE 1. Magnetic Onset Times

Station	Onset, October 5, 1963	Onset, January 16, 1964
College, Alaska	0845	0922
Sitka, Alaska	0900	0923
Meanook, Alberta	0847	0921
Tucson, Arizona	0904	0931
MacQuarie Island	0854	0927

than in Alaska. At Great Whale, Canada (L = 6.00), and its conjugate, Byrd, Antarctica (L = 7.25), the disturbance began about 0940, increased very slowly until 1000, and reached several decibels by 1050. The amount of absorption was quite variable at these stations during the disturbance, which persisted beyond 1200. At a lower magnetic latitude, onset time at Baie St. Paul, Canada (L = 4.03), and at its conjugate, Eights, Antarctica (L = 3.91), was approximately 0945, and the disturbance lasted about 2 hours.

Discussion. At approximately 0903 GMT on October 5, 1963, and 0937 GMT on January 16, 1964, the intensity of several VLF signals propagating on midlatitude paths at night began changing in an anomalous manner. These changes in signal level appear directly attributable to changes in the boundaries of the earth-ionosphere waveguide that supports VLF propagation. Since conditions at the earth's surface remain essentially constant, it is reasonable to assume that changes occur at the ionospheric boundary. At night, VLF waves are thought to have an effective reflection height of about 90 km, indicating that anomalous conditions in the ionosphere extend at least down to that level. A change in the ionization profile of the lower ionosphere can alter the nature of VLF signals received on the ground by changing the ionospheric reflection coefficient, by changing the effective reflection height, and by changing the amount of absorption occurring below the reflection level. The nature of the VLF perturbation presented here suggests that all three mechanisms may be involved.

The VLF anomalies were preceded as much as 15 minutes by magnetic bays over a large part of the earth's surface. The bays were strongest in the auroral zone in Alaska and Western Canada. (*Bates and Albee* [1965] have observed nighttime VLF anomalies in the auroral zone but have seen no definite correlation with magnetic bays.) The VLF anomalies were also preceded as much as 15 minutes by HF (riometer) absorption at several stations in and near the auroral zone (L values from about 4 to 9). This absorption, due to an increase in ionization in the lower D region, was apparently observed at higher latitudes than the VLF anomalies reported here.

It is not clear what causal relationship exists between the various types of phenomena discussed here. Perturbations were observed first in the auroral zone, with the onset of magnetic variation almost coincident with HF absorption. The two phenomena could arise from a common cause such as precipitation of auroral particles. With increasing time, the magnetic disturbance spread to lower latitude where the arrival corresponded reasonably well with the onset of midlatitude VLF anomalies. The question arises as to whether the auroral zone and midlatitude disturbances were independent, with perhaps a common cause, or whether the midlatitude disturbance depended on some mechanism to transfer auroral disturbance to that region. This latter possibility is discussed below.

A plausible transfer system described by *Martyn* [1953] and *Maeda and Sato* [1959] has been successful in explaining many features of magnetic storms. Ionospheric disturbances in the auroral zone are thought to modify the normal quiet-day S_q current system that circulates in the ionosphere above much of the earth's surface (see *Matsushita and Maeda* [1965]). The modified current system becomes established over a large geographic area, including midlatitudes, and the horizontal and vertical ionization drifts in the ionosphere over that area become modified. (Although the main circulating current is horizontal, vertical com-

TABLE 2. K_p Indices

Date	3-hr K_p Indices							
	1	2	3	4	5	6	7	8
October 5, 1963	1^+	2^-	1^+	3^+	2^-	1^o	3^o	1^+
January 16, 1964	3^-	3^+	3^+	5^o	4^o	5^o	4^o	3^o

ponents exist because of the horizontal component of the earth's magnetic field.) Modification of the vertical ionization drift behavior can be expected to alter the vertical ionospheric profile, and thus influence radio propagation. Although the transfer mechanism seems attractive for explaining the VLF anomalies reported here, much quantitative work needs to be done to assure that the time and space histories of the various disturbances are compatible, and is outside the scope of this paper.

Acknowledgment. In addition to the private communications already mentioned in the text, other sources of information were valuable in producing this paper. The many magnetometer records were provided by W. Paulishak of the U. S. Coast and Geodetic Survey. S. Horiwitz of Air Force Cambridge Research Laboratory was instrumental in providing riometer data from that organization. VLF data from Stockholm were collected by C. J. Abom of the Research Institute of National Defense and from Kiruna by S. Westerland of Kiruna Geophysical Institute. VLF data were collected by Stanford University at Stanford and Quebec City under contract ONR (225) 27. Facilities provided by U. S. Navy, Bureau of Ships, under contract NObsr 85271, were used by Stanford Research Institute to collect VLF data at Tracy.

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