Geomagnetic Disturbances and Associated Phase Anomalies of a VLF Radio Wave at Midlatitudes

Tadayoshi Hara and Koji Horiai

International Latitude Observatory of Mizusawa, Iwate, Japan

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Phase anomalies of VLF radio waves were investigated in relation to geomagnetic disturbances, using data obtained from the reception of the NLK station during 37 months from August 1970 to December 1974. The horizontal component of geomagnetic field observed at Memambetsu (Japan) together with the Ap index is used as an index of intensity of a geomagnetic disturbance. Primary storm effects on the phase anomalies during nighttime with an average value of 8 psec have a tendency to occur 2 hours later than the decrease of horizontal component of geomagnetic field with an average value of 70 gammas (hourly mean value). Storm after-effects which are the main features at midlatitudes continue for 3 days with large phase anomalies and further continue for about 5 days with small ones. Phase anomalies were observed during the daytime when the solar zenith angle was about 70° and observed during severe storm periods even with a solar zenith angle of 30°. Sudden phase anomalies were observed just after magnetic Pi pulsations.

1. Introduction

Among the many ionization sources in the D region, the ionization of nitric oxide by Lyman-α is thought to play the chief role during both the day and night periods, but various kinds of ionization changes are caused by solar flares. Phase disturbances which have short durations of about 45 min (Swanson and Kugel, 1973) are caused by increments of X-ray flux with wave length less than 8 Å in the daytime. Ionization changes by the precipitation of high energy particles detected by VLF radio wave measurements are known as Polar Cap Absorptions (PCA's) and Auroral Zone Absorptions (AZA's) (e.g., Ishii et al., 1967, 1973, 1976; Westerlund et al., 1969; Westerlund and Reder, 1973; Hakura et al., 1974). Studies of the storm after-effects which are the main features of midlatitude ionospheric disturbances were made by many authors (e.g., Lauter and Knuth, 1967; Belrose and Thomas, 1968; King and Fooks, 1968; Potemra and Rosenberg, 1973; Hara and Horiai, 1975; Montbriand
and Belrose, 1976; Wratt, 1976; Larsen et al., 1977; see Araki, 1974, for the geomagnetic storm effects at lower latitudes). The storm after-effects produce a maximum ionization increment in a period from 2 to 4 days after the time of maximum magnetic disturbances, and these effects often last for 10 days or more (Belrose and Thomas, 1968) but there is no direct correlation between the storm after-effects at midlatitude and PCA events at high latitude (Lauter and Knuth, 1967).

In this paper, we study relations between magnetic disturbances and phase changes of VLF radio wave (NLK 18.6 KHz) received at Mizusawa, Japan at a distance of 7,360 km from the transmitter. About half of the propagation path from the NLK transmitter (Jim Creek, Washington, USA, geographic coordinates, 121°35'W, 48°05'N, geomagnetic latitude 54°N) to Mizusawa (geographic coordinate, 141°08'E, 39°08'N, geomagnetic latitude 29°N) lies in the subauroral zone. The path is shown in Fig. 1 with precipitation flux contours of high energy electrons up to 1 MeV (Stassinopoulos, 1970).

The main phase of a magnetic storm is ascribed to equatorial ring currents, from which energetic particles precipitate during the recovery phase (Cornwall et al., 1970). During the recovery phase excess ionizations due to the high energetic particle precipitation will be detected in the northern portion of the propagation path between the NLK station and Mizusawa. In this paper, the precipitation effects on the VLF radio propagation are investigated in detail; another VLF phase change associated with magnetic pulsations is also reported.
2. VLF Phase Anomalies Observed in Nocturnal Periods

Cesium frequency standards are equipped at both the receiving and transmitting sites, but slight frequency differences were observed in nocturnal periods. A constant frequency offset was, therefore, removed by using phase correction data obtained from daytime propagation. The data were obtained during the periods August 1970 to June 1971, September 1971 to October 1971, April 1972 to October 1972, and August 1973 to December 1974. A temporary phase change is defined by the phase deviation from the monthly mean value during the days when no strong disturbances are observed. The negative sign of these phase changes means that the phase of received signals advance. VLF phase data were taken, using a Tracor Model 599E VLF Tracking Receiver, every 15 min with a resolution of 0.1 μsec. There could be an instrument error of the order of 0.5 μsec. Standard deviations of VLF phase data sampled at daily intervals during one month are ±0.5 μsec under the best conditions (i.e. in the

![Fig. 2. A monthly mean value (solid line) of the diurnal phase change of the NLK signal and phase variations (dotted line) of the NLK signal associated with the geomagnetic storm observed on December 14, 1970. The onset of the main phase of the geomagnetic storm is around 5h UTC. A large phase advance continued for two days and a small effect continued for four days.](image)
summer daytime) and are $\pm 8 \mu\text{sec}$ in the nighttime. Calibrations of the phase shift of the receiving system are made monthly by feeding a standard signal from a frequency synthesizer to the loop antenna.

An example of phase change observed during the magnetic storm of December 14, 1970 is plotted in Fig. 2. The sudden commencement of the magnetic storm (ssc) occurred at 0154 UTC* on December 14, 1970 and 3 hours later the main phase began. The storm after-effects on VLF phase change occurred on December 15 and 16 and were larger than the primary storm effects.

Associations of phase change with geomagnetic disturbances were examined here when magnetic disturbances of the horizontal component were larger than 100 gammas. Geomagnetic data from the Memambetsu Magnetic Observatory, Japan and 'Geomagnetic and Solar Data' from J. Geophys. Res., edited by J. Virginia Lincoln (1971–1975), were used as a reference for the disturbed magnetic field. Of thirty two storms, eleven storms were selected, as shown in Table 1 with deviations of the horizontal component larger than 100 gammas for the case where the growth period of the storm main phase was only at night. Other storms were excluded because fluctuations of their horizontal

Table 1. Geomagnetic storms in which the maximum deviations of the horizontal component observed at Memambetsu, Japan, are greater than 100 gammas and associated phase disturbances of the NLK signal are received during the nighttime at Mizusawa, Japan.

<table>
<thead>
<tr>
<th>Year</th>
<th>Beginning of the main phase</th>
<th>Maximum deviation of $H$-component (gammas)</th>
<th>Phase anomalies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>Month</td>
<td>Day</td>
</tr>
<tr>
<td>1970</td>
<td>8</td>
<td>17</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>16</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>7</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>21</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>14</td>
<td>5.0</td>
</tr>
<tr>
<td>1971</td>
<td>1</td>
<td>27</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>25</td>
<td>5.2</td>
</tr>
<tr>
<td>1972</td>
<td>4</td>
<td>28</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>9</td>
<td>4.4</td>
</tr>
</tbody>
</table>

* UTC (Coordinated Universal Time) is the time scale which is used for time dissemination, civil and other purposes. UTC has the same rate as TAI (International Atomic Time) and is controlled not to deviate from UT1 greater than 0.9s by introducing leap seconds. UT (Universal Time) is equivalent to UT0, UT1 and UT2 in the tolerance of a few hundredths of a second.
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Component last for a long time and beginning of growth period of the ring current is hard to identify. An average decrease of the horizontal component of the magnetic field associated with the received VLF phase advance is plotted in Fig. 3. Coincidence between the decrease of the horizontal component and the advance of the phase shift of the received signal can be clearly seen (see Fig. 3); that is, two hours after the commencement of the storm main phase, the phase of VLF signal has advanced by 8 µsec and the horizontal component has decreased by 70 gammas from the hourly mean value. The magnetic field decrease triggers the primary storm effect on VLF phase change, which is caused by high energy particle precipitations into the atmosphere. The storm after-effect lasted about a week or more as seen in comparison of the phase change with Ap index in Fig. 4. As pointed out by Belrose and Thomas (1968), the

Fig. 3. The geomagnetic horizontal component and corresponding phase deviations of the NLK signal. The geomagnetic horizontal component (solid line) is the average for the eleven storms from 1970 to 1972 which are listed in Table 1. The dotted line shows the corresponding phase deviations of the NLK signal from the monthly mean value received during the nighttime at Mizusawa (the primary storm effect). The negative sign means that the phase of the received signal is advanced.

Fig. 4. The geomagnetic disturbances (solid line) represented by the Ap index and the corresponding phase variations (dotted line) of the NLK signal received in nighttime at Mizusawa (the storm after effect). Both curves are for an averaged value of the eleven storms which are listed in Table 1.
storm after-effects persist for more than 10 days. In Fig. 4 we find that the
effect can be divided into a first strong phase that continues for about 3 days
and a following weak phase that persists more than 5 days.

3. Phase Anomalies Observed in the Daytime

During the moderate storm of April 21, 1970, for example, a direct mea-
surement of precipitation particle fluxes was made and showed that ionization
due to the precipitation competes with the total of all other daytime ionization
sources for the midlatitude D region (Gough and Collin, 1973). It may, how-
ever, be expected that large storms cause an anomalous phase advance even in
the daytime. On the NLK-Mizusawa propagation path, phase anomalies were
observed three times. Two of them were detected in the winter of 1970, on
November 21 and on December 14, when the solar zenith angles were between
60° and 80° which indicates a low photoionization state even at noon. Daytime
mean phase advances were 4 and 13 μsec for storms of November 21 and De-
cember 14, 1970 respectively (see Fig. 2). The third one was observed on
August 4, 1972 when the solar zenith angle was small (30°) but the magnetic
storm was exceptionally large and caused on the average, a phase advance of
8 μsec in the daytime period from 1930 UTC to 0300 UTC. An X-ray burst
was observed in the case of the August 4 event by the SOLARDI0-Explorer 44
but the X-ray flux of 1 to 8 Å already died down by 1800 UTC of the same
day (after Fig. 2 by Ohshio, 1974). Thus the phase anomalies seem to have
been caused by the particle precipitations associated with magnetic storms rather
than by the direct solar X-ray ionization.

4. Sudden Phase Anomalies Associated with Magnetic Pulsations

Irregular geomagnetic pulsations (Pi) are thought to be connected with
electron precipitations which drift in the magnetosphere (Obayashi, 1970), and
an association of ionization increment with geomagnetic pulsation was reported
(Campbell and Matsushita, 1962). Sudden phase anomalies (SPA's) are in-
vigated here with relation to Pi pulsations using rapid-run induction magne-
tograms of quality A and B observed at Memambetsu (KAKIOKA MAGNETIC
ObServatory, 1971–1975). Most of the Pi pulsations (121 times or 62% of the
total member) were observed during dawn or morning periods of 1974, but only
one SPA was observed. This fact indicates that SPA's do not usually happen
when the NLK transmitter is in the sun-lit periods; i.e., most of the detected
SPA's occurred in the northern region (λ~55°N) of the propagation path in
the nighttime (cf., Fig. 1). The selected 113 Pi pulsations which occurred along
the full nighttime propagation path are used to investigate the relation between the Pi pulsations and the VLF phase anomalies as given in Fig. 5. It will be seen in this figure that the start of the SPA averaged over 113 events agrees well with the onset of Pi pulsations. The average SPA effect has a fast rise time and short duration that resemble those of phase change caused by X-ray radiation in the daytime (Swanson and Kugel, 1973). Many authors pointed out that ionospheric absorption and bremsstrahlung X-ray effects are closely correlated with the Pi events (e.g., Campbell and Matsushita, 1962; Heacock and Hunsucker, 1977). We may thus conclude that the SPA's associated with Pi effects found in our VLF records are also caused by extra ionization due to particle precipitations of pulsating nature or due to the bremsstrahlung X-ray radiation associated with precipitations during Pi events.

Nighttime phase advances of about 10 μsec have frequently been observed. It is difficult, however, to attribute this to the effect caused by Pi pulsations, because the interference between the fundamental and harmonic waves can exist during the nighttime propagation of the 18.6 KHz signal, that is, the phase mixing of two wave mode produces a sudden phase advancement very similar to the Pi pulsation effects.

5. Discussion

Using LF absorption, Lauter and Knuth (1967) have pointed out that the storm after-effect is observed mainly after magnetic storms with an Ap index larger than 60. In our case, however, the storm after-effect was always observed after storms with an Ap index larger than 30. The difference of the threshold may be due to the differences of the propagation path and the method of phase comparison; in our case VLF waves pass through the region of energetic particle precipitation for about 3,000 km so that our method of the phase comparison is quite sensitive to ionization changes, while their results are based on
observations of the phase and field strength of LF and VLF radio waves which propagate over short distances.

Lauter and Knuth found that there is a strong decrease in the number and magnitude of absorption effects with decreasing latitude from 53°N southward. Recently, Larsen et al. (1976), from the data obtained by the satellite 1971-089A and ground based observations, also pointed out that the L-dependency of electron density distribution was remarkable between $L=2$ and $L=4$. Ionization changes by the precipitation of high energy particles are more effective at night than in the daytime in the subauroral zone. It then may be made clear which region affects the phase anomaly, by comparing the cases where the region in question is either in the daytime or nighttime when the main phase of a storm begins. There were two dawn storm events, one on April 14, 1971 and another on September 15, 1974 when Jim Creek was located on the day side and no phase changes occurred. On the other hand, there was a storm event on the evening of July 6, 1974 when Jim Creek was located on the nighttime side and phase changes were observed. These observations suggest that the storm after-effects are caused in the region around 55°N of magnetic dipole latitude in which the NLK-Mizusawa path of the VLF waves is parallel to the geomagnetic $L$ shell ($L=3$) at an altitude of 100 km. According to the result mentioned in section 4, it may also be suggested that electron precipitations are taking place in the northern part of the propagation path of the NLK waves.

It is reasonable that these ionization changes in the upper D region may increase the $f_{\text{min}}$ value observed by the vertical radio soundings. This discussion leads us to use $f_{\text{min}}$ data, only when these data are taken at a station which is located in the northern part of the NLK-Mizusawa path. Unfortunately no stations were found which actually satisfy this condition in the period when our VLF data analysis was made. If we select a station outside the longitudinal range of NLK-Mizusawa path we can use Ottawa station with $L=3.65$ which is located slightly north of the NLK station in the geomagnetic latitude. Primary storm effects and storm after-effects on $f_{\text{min}}$ observed at Ottawa station

![Fig. 6. The primary storm effect on $f_{\text{min}}$ value (dashed line) observed at Ottawa with the geomagnetic horizontal component (solid line) reproduced from the data given in Fig. 3.](image-url)
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are shown in Figs. 6 and 7. When the electron density increases anomalously in D layer, it make impossible to observe $f_{\text{min}}$ value itself by vertical sounding. We must then take into account the possibility that enhancements in the electron density are not always observed as an increase in $f_{\text{min}}$, although we can see a slight tendency for increase in $f_{\text{min}}$ during the storm period as given in Fig. 6. On the other hand, storm after-effects are clearly seen in Fig. 7, which is quite similar to Fig. 4 where the phase deviations of VLF radio waves due to the storm after-effects are shown. These observed facts indicate that the phase

![Image](attachment:geomagnetic_disturbances.png)

**Fig. 7.** Geomagnetic disturbances represented by the $Ap$ index (solid line) and the corresponding storm after-effect on $f_{\text{min}}$ value (dashed line) observed at Ottawa. The $Ap$ index is same data as used in Fig. 4.

![Image](attachment:phase_anomalies.png)

**Fig. 8.** Phase deviations from the monthly mean values of the NLK waves. The phase deviations are plotted against the $Kp$ index. Phase advances for large $Kp$ show that the SPA's are associated with the DR current system. The number of observations for each point are indicated.
deviations detected in the VLF radio waves are associated with the particle precipitation phenomena which are taking place around $L \approx 3$.

Relation of VLF phase data with the $Kp$ index is shown in Fig. 8 with the number of observations for each point indicated. The figure shows that the received phase advances for large $Kp$ index, and this suggests that phase anomalies are associated with the DR current as well as with electron precipitations during the decay process of the ring current system.

Recently, direct measurements of increase in electron precipitations by artificial satellites 1971-089A and ISIS-2 were reported by Larsen et al. (1977) and Wratt (1976) for the storms of December 1971 and August 1972, respectively. Montbriand and Belrose (1976) by analyzing the $N(h)$ profile obtained by the partial reflection method, also found that the maximum electron 'drizzle' occurred 2–3 days after the peak of the storm of December 1970. The two of the storm after-effects analyzed by these authors coincide with two of our eleven storm after-effects which have the VLF phase anomalies as discussed above (the phase data of VLF reception in December 1971 were not obtained). Thus, the VLF phase anomalies reported here are due to the precipitation effect.

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