Earth Induction Effect for Pc 5 Pulsations Observed by Unmanned Magnetometer Network Near Syowa Station, Antarctica

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Unmanned magnetometer network observation was carried out near Syowa Station, Antarctica from early spring to summer seasons of 1988. The network consisted of three remote stations, H100 (80 km south of Syowa Station), Skarvsnes (50 km south-west of Syowa Station), and site F22 (20 km east of Syowa Station). From a cross-correlation analysis of Pc 5 events observed during the magnetometer operation, we found an unusual phase characteristics in vertical component of F22-Syowa pair, which can not be interpreted by a Pc 5 incidence for the ground conductivity with horizontally uniform distribution. We carried out a numerical simulation of Pc 5 incidence for the ground conductivity with a local conductivity anomaly, and based on that model calculation, we can infer a possible effect of local earth currents that may appear in the cross-correlation analysis for such a short separation.

1. Introduction

The ground measurement of the magnetic field signals from the upper atmosphere includes two parts, namely signals of incident and reflected from the ground, where the reflected signals are interpreted as being generated by earth induction currents (Price, 1967). The amplitudes and phase of the incident signals are modified significantly, if the ground measurement was carried out in the proximity of the geoelectric inhomogeneity (conductivity anomaly) (Rankin and Reddy, 1972; Hughes, 1974). Parkinson (1959) studied the magnetic fluctuations in the range less than 60 min, and found a vector that infers the observed direction of the high conductivity oceans, and the vector has been referred to as the “parkinson vector”. The studies of distribution of conductivity anomaly by use of the geomagnetic field fluctuations were carried out by Rikitake (1964) utilizing data obtained in Japan, and by Schmucker (1964) using data from network stations in southwestern US, where they considered the incident signals as a uniform ionospheric currents. While in high latitudes, the auroral electrojet currents were utilized to study the earth induction effects, where the jet currents with finite longitudinal width were assumed to be a source current in the ionosphere (Mareschal, 1976). For both cases, a simple source current in the ionosphere was assumed to calculate and obtain the response of the earth. In high latitude, however, geomagnetic signals are affected more or less by the plasma dynamics in the magnetosphere, and one of the basic features in the magnetosphere is standing oscillations of the magnetic field lines. The standing oscillations were investigated extensively for Pc 5 pulsations by utilizing ionospheric radar measurements (Walker et al., 1979; Samson et al., 1992) and by ground magnetometer network measurements (Samson et al., 1971; Rostoker and Lam, 1978; Saka et al., 1982). As a result, ionospheric signature of the Pc 5 pulsations and mechanism of the atmospheric transmissions of the signals are well understood (e.g., Hughes, 1983).

In this report, we carried out a simulation of the earth induction effect by taking account of the standing field line oscillations as incident signals at the ionosphere. We discuss, based on the computer simulation, how those incident signals are modified on the ground surface by the local conductivity anomaly. The simulation results were utilized to interpret the Pc 5 signals measured by unmanned ground magnetometer network in Antarctica conducted in 1988 by JARE 29 team (Saka et al., 1990).
Fig. 1. A schematic illustration of ionospheric current system associated with Pc 5 pulsation. Distributions of the Pedersen current (arrows) and its divergence (circles) (field-aligned current) are shown. Horizontal coverage of the distribution is 2000 km in longitudes and 1000 km in latitudes. The vector of the Hall current is right angles to the vector of the Pedersen current. At t = 0, eastward Hall current was in the center of the latitudes (single current system), and at t = 1/4 cycle, eastward (westward) Hall current in poleward (equatorward) side of the center (double current system). The Hall current encircles counterclockwise (clockwise) the upward (downward) field-aligned current region.
2. A Model of Pc 5 Pulsation

Before proceeding to the discussion of the model calculation, we briefly describe the ionospheric source associated with Pc 5 pulsations. It has been suggested that the resonant oscillations of the geomagnetic field lines (hereafter referred to as standing oscillations) recorded on the ground magnetometer are caused by ionospheric Hall currents (e.g., Hughes, 1983). This leads to the condition that the ground magnetic vector is parallel to the Pedersen current vector right above in the ionosphere. Based on this consideration, we reproduced the ionospheric current system of Pc 5 pulsations in Fig. 1 by utilizing the result of the cross correlation analysis of the IMS ground magnetometer network data (Saka et al., 1982). The network was consisted of 18 ground stations, which spans 63° to 79° in geomagnetic latitudes (1600 km) and 266° to 326° in geomagnetic longitudes (2800 km). The amplitude and phase difference obtained by cross correlation analysis between neighboring stations were interpolated to obtain a smoothed amplitude and phase structure. In the figure, the Pedersen currents and divergence of the Pedersen currents (i.e., the field-aligned currents) obtained from the smoothed structure are plotted at a consecutive cycle of the oscillations (t = 0, t = 1/8 cycle, and t = 1/4 cycle). It is shown that the oscillation of the ground signals is not attributable to the oscillation of the ionospheric current intensity but to the poleward convection of the current system (Walker et al., 1979; Greenwald and Walker, 1980).

Observationally, however, the ionospheric current system described above reproduced reasonably well the H component (north-south component) of the ground measurements, while the D component (east-west component) was poorly reproduced (Walker et al., 1979). It is suggested that the effect of field-aligned current may not be neglected for the estimation of D component amplitude even on the ground (e.g., Brekke et al., 1974). For this reason, we look at the H component and discuss model ionospheric currents flowing in east-west direction. This restriction does not bring about a significant limitation for the modeling of the ionospheric Pc 5 source, because the intensity of north-south ionospheric current was estimated to be only 30% of that of east-west current (Saka et al., 1982).

To obtain the surface values of the magnetic fields on the ground, two dimensional numerical simulations were carried out in 400 km (in north-south) x 325 km (in vertical) area (41 x 41 grid size), based on the computer simulation code of Jones and Pascoe (1971). In vertical, the ionosphere was set at 100 km above the ground level, and the depth of the earth was 225 km. The ionospheric current source was assumed to be localized in the horizontal direction, x (north-south direction, center is at x = 0), in a form,

\[ \exp\left[-(\xi \cdot x)^2\right] \cdot \exp[i \cdot (\phi(x) - \omega \cdot t)]\]

where \( \xi \) is a north-south scale of the signal amplitudes (2 \times 10^{-7} \text{ cm}^{-1}), \( \phi(x) = (\pi/2) \cdot \tanh(2\xi \cdot x) \) is a north-south phase profile of the signals (i.e., standing oscillation of the field lines), and \( \omega \) is a wave frequency (2.5 mHz). We assumed that the source is uniform in east-west direction. We utilized the result of the radar measurement of Pc 5 pulsations to estimate the parameters \( \xi \) and \( \phi(x) \) in the above expression (Walker et al., 1979; Samson et al., 1992). First of all, we simulated the amplitude and phase profiles at ground level for the case of uniform ground conductivity distribution (1 \times 10^{-14} \text{ emu}). The results are illustrated in Fig. 2, where the amplitudes for the horizontal and vertical component show a maximum at the center (x = 0) with 140° and 260° phase change across the peak. These results are in accord with the ground measurement by the magnetometer network (Saka et al., 1982).

We attempted to simulate the response of the Earth induction current where the conductivity strike is assumed to run parallel to the source currents in the ionosphere. For this purpose, high conductivity block (conductivity anomaly; 1 \times 10^{-11} \text{ emu}) was embedded between 60 and 120 km away from the center and between 0 and 10 km below the surface level as is marked by the block in Fig. 3, wherein the anomaly is assumed to be distributing uniformly in east-west direction. The simulated profiles for the amplitude
and phase are illustrated in the figure as well. For this case, there appeared additional peak of the amplitudes for both the components at the left side edge of the conductivity anomaly (not right at the center of the anomaly but shifted toward the Pc 5 center). The signals caused by the conductivity anomaly were much larger than the original peak at the center. The phase structure is affected by the conductivity anomaly as well. In order to understand the effect of the conductivity anomaly, we plotted in Fig. 4 north-south profiles of the horizontal and vertical components at a specific cycle of the oscillations, i.e., $t = 0$ and $t = 1/4$ cycle. The north-south profiles for the case of the uniform conductivity distribution are plotted together for the reference, and differences of the profiles from the reference are shown by the hatched area. At $t = 0$, the ionospheric currents are located at the center flowing into the paper, and at $t = 1/4$ cycle, the
Earth Induction Effect for Pc 5 Pulsations Observed by Unmanned Magnetometer Network

Fig. 4. Latitudinal profiles of the field variations of $BX$ (H component) and $BZ$ (vertical component) components for two different cycles of the oscillations, $t = 0$ and $1/4$ cycle. At $t = 0$, the ionospheric current forms a single current system, and at $t = 1/4$ cycle, it forms a double current system as is shown in the top of the figure (see Fig. 1). Those profiles with and without the conductivity anomaly are superimposed, and the hatched area is caused by the local earth currents induced by the conductivity anomaly which is marked by the block in the bottom of the figure. The current polarity of the local induction currents is shown above the anomaly.

The ionospheric current forms a double current system with opposite current polarities as are illustrated in the top of the figure (see also Fig. 1). The induction currents with a current polarity opposite to the ionospheric currents right above were generated in the anomaly block for both cases as illustrated in the portion above the anomaly block, and they produce the anomaly part of the field variations at the ground level as hatched in the figure. We could conclude from these considerations that the earth induction currents flow in the high conductivity section with current polarities to be consistent with an image currents of the overhead ionospheric currents. The ground effect of the local induction current may weaken, however, when the source currents being localized in latitudes leave away from the anomaly section. In summary, the polarity of the $BZ$ component reversed with respect to the center of the additional image current, while for the $BX$ component only the amplitudes were affected. Thus, a rapid phase variation across the anomaly currents took place only for the $BZ$ component, as was illustrated in Fig. 3.

In below, we introduce the unmanned magnetometer network observations that were carried out in the area near Syowa Station, Antarctica, and show an abnormal distribution of Pc 5 signals measured by this magnetometer network. We attempt to interpret these observations by the local current effect described above.

3. Observations and Interpretation of the Results

Unmanned magnetometer observation has been carried out in the area near Syowa Station, Antarctica, from winter to summer of 1988. Detailed description of the unmanned system was presented elsewhere (Saka et al., 1990). As can be seen in the map in Fig. 5, the network consisted of four stations (SYOwa, SKaRvnes, H100, F22), while three of them (F22, SKR, H100) were unmanned remote stations. Unfortunately, magnetometer observations using all four stations were not attempted due to a limited capability of the deployment. In this report, we utilize the Pc 5 event of Sep. 1, 1988 observed by SYO-F22 pair, wherein an apparent effect of the local induction currents can be seen in spite of this short inter-station distance of 20 km. While for SYO-SKR-H100 pair, no significant local induction effect has been recorded during Pc 5 event of Oct. 6, 1988 (not shown).
Fig. 5. Map showing the distribution of the unmanned remote sites (SKARVSNES, H100, F22).

Fig. 6. Magnetometer records at SYO and F22 during the periods from 0400 UT to 0700 UT of September 1, 1988. Pc 5 events were recorded during the interval, 0530–0630 UT. Upper trace is for F22, and lower trace for SYO.
Earth Induction Effect for Pc 5 Pulsations Observed by Unmanned Magnetometer Network

SYO, H-Component for 01/09/1988

SYO, D-Component for 01/09/1988

SYO, Z-Component for 01/09/1988

UT

Fig. 7. Log power plots for SYO dynamic spectra during the interval shown in Fig. 6. The upper panel is for H component, middle panel is for D component, and the lower panel is for Z component. Pc 5 event was recorded in the center of each panel.
Fig. 8. Same as Fig. 7 but for F22.
Fig. 9. Cross phase analysis between F22 and SYO for the $H$ (upper panel), $D$ (middle panel), and $Z$ (bottom panel) components. White for in-phase portion, while black for out-of-phase portion. Note that the range of the phase is limited between $-100^\circ$ and $+100^\circ$. The phase difference is measured positive, if F22 leads SYO.
Pc 5 pulsations were recorded by SYO-F22 pair during 0530–0630 UT of Sep. 1, 1988 (Fig. 6). To investigate the spectral characteristics of the event, we performed a cross spectral analysis by FFT method for the above interval, and dynamic power spectra are shown in Fig. 7 for \( H \) (positive north), \( D \) (positive east), and \( Z \) (positive vertically downward) components of SYO, respectively. In Fig. 8, those of F22 are presented. The Pc 5 event showed power maximum in the range of 3.0–3.5 mHz for all components at both stations. We estimated the cross phase for the \( H \), \( D \), and \( Z \) component. The results are shown in Fig. 9. To emphasize the results, the range of the phase value was limited between \(-100^\circ\) and \(+100^\circ\). Because, it loosed the information about \(+\) (F22 leads SYO) and \(-\) (SYO leads F22), we referred to the color plot out when needed. A characteristic noted for the FFT result is a larger phase difference in the \( Z \) component than the rest of the components. The phase difference amounted as much as \(+100^\circ\). Indeed, the \( Z \) for F22 apparently leads that of SYO as can be inferred from the time series plots in Fig. 6. For example, an estimation of IMS network results of Saka et al. (1982) suggests that phase of the \( Z \) component could change as much as \(45^\circ\) for 100 km separation. The phase difference is definitely too large for such a short distance of the station separation (20 km). It is normal, on the other hand, that the horizontal components, \( H \) and \( D \), showed a small phase change in such a short distance (Saka et al., 1982). As was inferred by the model simulation, the local earth current flowing at a shallower depth modifies the phase in \( Z \) while for the horizontal the modification is less significant. Therefore, observed phase characteristics might be accounted for only by introducing the local earth current flowing at a shallower depth near the F22-SYO pair. The simulation suggested that the amplitude distributions are affected by the local earth current as well. Indeed, the observation suggests a larger amplitudes for the \( H \) and \( Z \) components for F22 than those for SYO; a factor of 2 for the ratio of the spectral power. Such a contrast was not detected for the \( D \) component which is supposed to be determined primarily by the incident signal structure and be free from the anomalous earth currents. The result indicates that F22 may locate closer to the local earth induction currents.

From the spectral analysis for Sep. 1 event, we could conclude that the local earth currents that had brought about a significant modification of the vertical phase appeared in the latitudes close to the Syowa Station (66.2°, 71.8°E in geomagnetic coordinates). We could not determine, however, whether a coast line effect from a sea or any other local conductivity anomalies which we do not know yet produced the observed anomaly part of the field changes. A depth of the anomaly current and its proximity to the pulsation center may affect the intensity of the image currents, and those conditions influence the surface value significantly. The effect of the local induction currents on the ground measurements may change from one event to another, because the longitudinal width of the ionospheric currents associated with the field resonance in the magnetosphere is narrow (~100 km) and they move in longitudes depending on the wave periods according to the resonance mechanisms.

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