Occurrence Characteristics of the Preliminary Impulse of Geomagnetic Sudden Commencement Detected at Middle and Low Latitudes

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The occurrence frequency of preliminary impulse (PI) of geomagnetic sudden commencements was statistically studied using the geomagnetic records of H-component at Fredericksburg (FRD; 49.0° geomagnetic latitude) and San Juan (SJG; 29.2°). In the daytime, positive PI predominantly occurs before noon and negative PI in the afternoon. These features, which are the same as those of high-latitude PI, indicate that high-latitude ionospheric currents responsible for PI extends toward middle and low latitudes. Almost all PIs detected in the nighttime are negative at FRD though the occurrence rate is much smaller than in the daytime. The diurnal variation of the occurrence rates of PI shows a drastic seasonal change at SJG, which is probably caused by a seasonal variation of the ionosphere. No correlation between the occurrence rates and the solar activity was found at either observatories. Ionospheric currents which are driven by a pair of field-aligned currents were numerically calculated on the assumption of the stationary state, and the geomagnetic field variation caused by the three-dimensional currents is simulated. Although the symmetric distribution of the field-aligned currents with respect to the noon–midnight meridian has been assumed, the calculated diurnal variation of magnetic field exhibits a severe deflection from the symmetry in middle and low latitudes.

1. Introduction

At the beginning part of a geomagnetic sudden commencement (SC), the main impulse (MI) is often preceded by the preliminary impulse (PI) with a time scale about one minute. Occurrence of PI strongly depends on the latitude and the local time of observation points.

In high latitudes, the overhead equivalent current responsible for PI consists of a pair of vortices the foci of which are located around the dayside auroral zone. The current direction of the dawnside vortex is counterclockwise and that of the duskside vortex is clockwise in the northern hemisphere (Nagata and Abe, 1955). PI is frequently observed also in a narrow region along the dip equator; the sense of the geomagnetic H variation in the region is southward in the daytime (Matsushita, 1960; Rastogi, 1971; Araki, 1977) and northward in the nighttime (Araki et al., 1985). Araki (1977) showed that PI occurs almost simultaneously in both high latitudes and the equatorial region, and concluded that the equatorial PI has the same origin as that observed in high latitudes. At high latitudes the equivalent current system of MI consists of twin-vortices as the same as PI but with the reversed direction of the flow, whereas the equivalent current in low latitudes is nearly a zonal flow (Obayashi and Jacobs, 1957).

Based on these results of observation, Araki (1977) separated the geomagnetic variation of an SC, $D_{sc}$, into three parts;

$$D_{sc} = DL_{mi} + DP_{mi} + DP_{pi},$$

where $DL_{mi}$ and $DP_{mi}$ are the parts of MI originating in low and high latitudes, respectively, and $DP_{pi}$ is the geomagnetic disturbance of PI which originates in high latitude and spreads instantaneously.
toward the equator.

Araki (1977) explained the mechanism for each part as follows: sudden compression of the magnetopause due to the interplanetary shock wave enhances the geomagnetic field and produces a dusk-to-dawn electric field in the magnetosphere. The electromagnetic field is propagated tailward in the magnetosphere as a transverse hydromagnetic wave. This is observed as the global increase of the magnetic field on the Earth \((DL_{mi})\). At the same time the dusk-to-dawn electric field is propagated as a compressional hydromagnetic wave along the geomagnetic lines of force down to the high latitude ionosphere (Tamao, 1964). The electric field drives the twin-vortex type Hall current in the ionosphere, and this current is responsible for the \(DP_{pi}\). After the interplanetary shock wave sweeps the magnetopause, the magnetospheric convection is enhanced. The electric field associated with the enhanced convection is transmitted along geomagnetic lines of force and generates the ionospheric currents at high latitudes. The main impulse observed at high latitudes is primarily attributed to the currents produced by the enhanced convection \((DP_{mi})\).

The \(PI\)-associated dusk-to-dawn electric field imposed on the high latitude ionosphere is propagated toward the equator and generates a westward (eastward) ionospheric current along the dayside (nightside) equator. This is why the magnetic variation of \(PI\) observed both at high latitudes and the equator is expressed as a term, \(DP_{pi}\). Thus the intermediate region, the middle and low latitudes, would play a principal role in the equatorward transmission of the \(PI\) source field as an "electrical wire", which connects the high latitudes and the equator. The occurrence characteristics of \(PI\) in middle and low latitudes can give us an important clue to know how the electrical coupling can be attained.

\(PIs\) at these latitudes, however, have not yet been fully studied because the amplitude of \(PI\) decreases rapidly with decreasing latitude (Nagata, 1952) except for along the equator: Matsushita (1960) investigated SCs during the IGY period and depicted rough patterns of diurnal variations of occurrence frequency of two types of \(PI\) (\("SC and SC\" denoted in his paper), but only qualitative results were derived from the small number of SCs. Sano (1964) deduced the diurnal variation of the occurrence frequency at several observatories using data for ten years. His statistics are, however, also short of the number of samples of \(PI\) because he used normal-run magnetograms, through which the identification of \(PI\) is difficult for the small amplitude in low latitudes. Consequently the local-time variation of the occurrence of each type of \(PI\) is remains to be investigated until now. Moreover neither the seasonal nor year-to-year variations of the occurrence, which would reflect the importance of the ionosphere in the electrical coupling, has not been analyzed for the \(PI\) in these latitudes.

In this paper, we investigate SCs for a long period recorded on rapid-run magnetograms at middle and low latitudes and examine the diurnal variation of occurrence rate of \(PI\), including the seasonal and secular variations. Further, a numerical simulation for the magnetic field perturbation of \(PI\) is performed and the results are compared with those of the statistical analysis.

2. Data Analysis

Using rapid-run magnetograms, we have examined whether the trace of \(H\)-component of each SC has a \(PI\) or not. The records of two observatories, Fredericksburg (FRD; 49.0° geomagnetic latitude) from 1957 to 1975 and San Juan (SJG; 29.2°) from 1966 to 1979 are used for the analysis, which are all the obtainable rapid-run records of the observatories. These observatories are located along almost the same meridian (282.6° and 293.9° geographic longitude, respectively). We have analyzed SCs before 1975 listed by Mayaud (1973) and Mayaud and Romana (1977) and those after 1976 reported in the Solar Geophysical Data by more than two observatories.

The traces of the \(H\)-component of two SCs are drawn as examples of \(PI\) in Fig. 1. The left two traces show an SC observed simultaneously at FRD (top) and SJG (bottom) in the morning. The abrupt increases at both stations represent the positive \(PI\). At FRD the \(PI\) is followed by a decrease below the level before the onset, which would be the effects of \(DP_{mi}\). At SJG the variations of high latitude origin \((DP_{mi} and DP_{pi})\) are smaller than at FRD. The right two traces in Fig. 1 show an SC observed in the evening. A clear negative
Occurrence Characteristics of the Preliminary Impulse of Geomagnetic Sudden Commencement

September 18, 1974

March 23, 1969

FRD

SJG

20nT

14:25 UT 14:35 14:45 18:20 UT 18:30 18:40

Fig. 1. Geomagnetic $H$ variations of two SCs with the positive (left) and negative (right) PIs. The top and bottom traces are drawn from the rapid-run magnetograms of Fredericksburg (FRD) and San Juan (SJG), respectively. The PI is indicated by an arrow.

FRD-H 1957-75 TOTAL

SJG-H 1966-79 TOTAL

Fig. 2. Diurnal variation of the occurrence rate of PI in $H$-component of FRD and SJG (upper and lower panels). The rate is derived in every 3-hour magnetic local time. Solid and dashed lines represent the rate of positive and negative PIs, respectively.
PI preceding the positive variation is detected at both observatories. The sense of the PIs, positive in the morning and negative in the evening, is consistent with the statistical analysis by Matsushita (1960) and Sano (1964).

To study the occurrence characteristics of PI statistically, we calculated the occurrence rates, $P_+$ and $P_-$, for the positive and the negative PIs in the $H$-component;

$$P_+ = N_+ / N, \quad P_- = N_- / N,$$

Fig. 3. Diurnal variation in the occurrence rate of the positive and negative PIs at FRD in summer (upper panel), in equinoxes (middle panel), and in winter (lower panel), respectively. Solid and dashed lines represent the rate of positive and negative PIs, respectively.
where $N_+$ and $N_-$ are the numbers of SCs accompanying the positive and the negative PI, respectively, and $N$ is the total number of the analyzed SCs (sum of SCs both with and without PI). SCs on which the judgment is difficult have been excluded from these counts. $P_+$ and $P_-$ are calculated separately for FRD and SJG. The numbers of the analyzed SCs for FRD and SJG are 462 and 301, respectively.

Figure 2 shows the diurnal variations of $P_+$ and $P_-$ of FRD and SJG (upper and lower panels). The rates are derived in every 3-hour magnetic local time and $P_+$ and $P_-$ are represented by solid and dashed lines, respectively. This figure shows that, in the daytime, the positive PI predominantly occurs in the forenoon and the negative PI in the afternoon at both stations. This feature can be interpreted by an extension of the ionospheric current vortices in high latitudes toward the lower latitudes; the current

Fig. 4. Same as Fig. 3 but for PIs at SJG.
flowing in counterclockwise (clockwise) direction in the morning (afternoon) sector produces a positive (negative) geomagnetic $H$ variation on the ground on the lower latitude side of the focus of the vortex. Peak values of $P_+$ and $P_-$ at FRD are almost the same and both profiles are symmetric to the noon in the daytime. At SJG, however, the peak value of $P_+$ (53%) is much larger than that of $P_-$ (19%), and $P_+$ is comparable
to $P_-$ still in the postnoon sector. As exemplified in Fig. 1, at SJG, the negative PI is usually less discernible than the positive PI. The magnitude of $DL_{mi}$-part variation is probably larger in lower latitudes, while the magnitude of PI is smaller. The negative PI will, therefore, become invisible due to the positive variation predominant in low latitudes, which is likely to be the reason for the imbalance between $P_+$ and $P_-$ at SJG. It is noteworthy that, however, the positive PI would be detected at SJG with highest probability just before noon and negative PI just after noon, and that the form of both profiles is similar and symmetric to the noon in the daytime although the amplitudes of the profiles are different. This symmetric profile in the daytime is found also at Tucson (40.3° geomagnetic latitude), which is located in the intermediate latitude of FRD and SJG (Sano, 1964).

In the nighttime the occurrence rate of PI is much smaller than in the daytime at both stations. The upper panel shows that negative PI is predominant at FRD all night which is remarkably contrast with the balanced occurrence in the daytime. This biased occurrence of PI in the nighttime is not seen at SJG.

Figures 3 and 4 represent the diurnal variation for each season at FRD and SJG, respectively. The upper, middle and lower panels of each figure show the profiles of the occurrence rate of PI in summer (J-months; May, June, July, and August), in equinoxes (E-months; March, April, September, and October) and in winter (D-months; November, December, January, and February), respectively. Symmetric distribution in the daytime at FRD is not varied with seasons at all as seen in Fig. 3. Figure 4, however, reveals a drastic seasonal change in the diurnal variation of the rate of both positive and negative PIs at SJG; in contrast with Fig. 2, the profiles of $P_+$ and $P_-$ in summer are not so imbalance on both sides of the noon in the daytime although the peak value of $P_+$ is still larger than that of $P_-$. In equinoxes or winter, on the contrary, $P_+$ in the morning takes a larger value and, especially in winter, almost only positive PI appears throughout a day. The seasonal dependence, which is not seen at FRD, cannot be explained by seasonal changes in amplitude or location of the source field incident in higher latitudes, but probably reflects the seasonal variation of the ionospheric structure. The equatorward propagation of PI-field in high latitudes may be controlled, for example, by the ionospheric conductivities.

In Fig. 5 we show the annual occurrence rate of PI observed in the daytime (6–18 h magnetic local time) at each station. The upper and middle panels represent the variations in the occurrence rates for H-component at FRD and SJG, respectively, where the rates were derived in every 2-year. The lower panel shows the variations of the monthly-mean values of the International Sunspot Number (solid line) and the 10.7 cm solar radio flux (dashed line) from 1957 to 1979, which are standard indices representing the level of the solar activity. It is obvious in this figure that the occurrence rates at each station have no correlation with the sunspot number or the solar flux. This feature was also found at Kakioka (26.8° geomagnetic latitude) by Sano and Saito (1984) who investigated SCs that appeared during 58 years. They found that the secular variation in the occurrence rate of SC* (negative PI in the H-component) is poorly correlated with the sunspot number although the numbers of SC and SC* themselves show clear correlations with it. Thus it seems to be a common feature in the middle and low latitudes that the PI-occurrence rate does not have clear dependence on the solar activity. However, this fact contrasts with the results for the equatorial PI. Rastogi (1971) examined the numbers of SC and SC* at Kodaikanal (0.9° geomagnetic latitude) during 1949–1968. Clearly the secular variation in the occurrence rate of SC* follows the variation in the sunspot number although this was not explicitly stated in his paper. The secular variation of the occurrence rate at Guam (4.7° geomagnetic latitude) is also found to resemble the solar cycle variation as shown by Araki (1977) and Takeda and Araki (1985).

3. Model Calculation

As was mentioned in Section 1, PI is caused by the transverse hydromagnetic wave propagated along geomagnetic lines of force. The wave carries the field-aligned currents and dusk-to-dawn electric field in the magnetosphere (Tamao, 1964). When the wave-front reaches the ionosphere, the Hall currents and the Pedersen currents that are connected with the field-aligned currents are generated in high-latitude ionosphere by the incident electric-field. In our simulation, we have assumed the current system
responsible for PI to be stationary. In that case the static magnetic perturbation of PI is produced by a three-dimensional current system that consists of a pair of field-aligned currents and ionospheric currents driven by the field-aligned currents.

Assuming an appropriate distribution of the field-aligned current, a current continuity equation is numerically solved by using the method of Takeda (1982) to obtain the distribution of the three-dimensional ionospheric currents. In the calculation, we have used a model of equinoctial conductivities of the ionosphere based on the International Reference Ionosphere. We calculated the magnetic field distribution on the ground generated by the field-aligned and ionospheric currents applying the Biot-Savart law. The field-aligned currents are set to flow into the area centered at 70° latitude and 14 h local time on the upper boundary surface of the ionosphere (1000 km altitude) and to flow out from the same latitude at 10 h local time. They are distributed symmetrically with respect to the noon-midnight meridian, referring to the results obtained by Sano (1964); he investigated 181 SCs at College, which would be located near the source-current region, and obtained the symmetric distribution of occurrence frequency of the SC accompanying either positive or negative PI (SSC* or iSSC* in his notation).

Figure 6 shows the local time variation of the calculated magnetic H-component on the ground at 10-degree latitudinal intervals. If the ionospheric conductivity is globally uniform, twin-vortex currents are expected to flow symmetrically on each side of the noon-midnight meridian. Then the magnetic H variation on the lower latitude side of the source region will be demarcated by the noon-midnight meridian; positive in the prenoon sector and negative in the postnoon sector corresponding to the opposite direction of east-west currents on each side. As can be seen in this figure, however, profiles in the daytime below 70° latitude show severe deflection from the symmetry. The negative-field region in the duskside intrudes into the morning sector in the daytime and the positive-field region almost vanishes below 40° latitude. As for the equator (0° latitude) the magnetic field is negative in the daytime and the amplitude is much larger than at low latitudes because of the equatorial enhancement of the ionospheric Cowling conductivity. Though the westward current responsible for this magnetic variation is supplied from the symmetric field-aligned currents at high latitude through the ionospheric Pedersen currents, the peak is located at around 11 h local time. This is consistent with the results of the two-dimensional simulation by Tsunomura and Araki (1984).

Because the distribution of the field-aligned currents is assumed to be symmetry, this asymmetry is certainly due to the non-uniform distribution of the Hall conductivity. Ionospheric Hall currents flowing in a day-night direction cause charge accumulation through the conductivity gradient. The charge deforms the distribution of the dusk-to-dawn electric field driven by the pair of field-aligned currents, and the electric field in turn varies the distribution of the ionospheric currents. Figure 6 shows that the inhomogeneous ionosphere causes the clockwise rotation of the twin-vortex ionospheric current system, and the duskside current vortex expands toward the dawnside and dayside. We tried other models of distribution of the ionospheric conductivities representing several levels of the solar activity, but above features were commonly seen also in the results.

The dawn-dusk asymmetry seen in the stationary model has been reproduced also by simpler models: Lyatsky et al. (1974) calculated the equivalent currents assuming that the ionosphere is a thin spheric shell. In the case when the distributions of the height-integrated Hall and Pedersen conductivities are homogeneous, the equivalent current flow is symmetric to the noon–midnight. In the case when the conductivities have a discontinuity at the dawn-dusk meridian, however, the flow pattern deflects and the current vortex in the duskside becomes larger than the dawnside one, even if the conductivities are homogeneous at the day and night sides. These results similar to ours indicate that a day-night gradient of ionospheric Hall conductivities makes the severe dawn-dusk asymmetry of the magnetic perturbation on the ground.

In Fig. 6 the nocturnal H-component level is biased to negative value at all latitudes, which agrees with the predominance of $P_-$ in the nighttime at FRD (Fig. 2). The negative $H$ perturbation is mainly attributed to the field-aligned currents on the dayside because ionospheric conductivities are small on the nightside and contribution from the ionospheric current is negligible.
4. Discussion

The DP2 geomagnetic variation, first proposed by Nishida (1968a), is originating in a convection in the magnetosphere. The dawn-to-dusk electric field produced by the convection is transmitted to the high-latitude ionosphere along geomagnetic lines of force. Then ionospheric currents are driven in a way similar to the case of currents for PI but with a reversed direction. Namely the equivalent current of DP2 at high latitude also consists of a pair of vortices. It is noteworthy that the duskside vortex of DP2 is much larger than the dawnside one and intrudes into the prenoon sector in the daytime (Nishida, 1968a, b). A pair of current vortices with the similar imbalance is found for the MI of SC. When the convection in the magnetosphere is intensified just after the magnetospheric compression of SC, the enhancement of the DP2-type magnetic variation is detected on the ground as the DPmi (Araki, 1977); the shape of the equivalent current system is almost the same as that of DP2, and has the asymmetry with respect to the noon-midnight meridian (Obayashi and Jacobs, 1957). These features of the DP2 and MI are also seen in the result of our simulation (Fig. 6) although the flow directions of the current systems are opposite to that of the simulated current flow. The agreement with the result of calculation infers that these phenomena can be well described by the stationary model.
Our analysis of PI, on the other hand, has revealed the LT variation of the occurrence different from the calculation (Figs. 2 and 6). The profiles of \( P_+ \) and \( P_- \) are symmetric to the noon at middle (FRD) and low (SJG) latitude, whereas the calculated magnetic field variation shows the intrusion of duskside current vortex into the morning sector. The disagreement cannot be attributed to the model of the field-aligned currents used in the calculation; though we used the symmetric distribution of the field-aligned currents with respect to the noon-midnight meridian, some other models of the currents biased to the evening sector could be selected so that the magnetic perturbation on the dayside becomes more symmetric in the middle or low latitudes. In that case, however, the distribution of the magnetic field in the source-current region becomes asymmetric in higher latitudes, which is inconsistent with the result of Sano (1964). For the reason, it is difficult to attribute the disagreement to the model of the field-aligned currents.

We offer here two possible reasons why the asymmetry appears in the calculation and not in the observation. One is the inaccuracy in the model of the ionospheric conductivities. In fact, the distributions of the conductivities could affect the result of the calculation. However, this is unlikely because, as far as the day-night contrast of the conductivities exists, the asymmetry in the dayside ionosphere is inevitable in the stationary current system as demonstrated by Lyatsky et al. (1974). They calculated the distributions of the ionospheric currents induced by a pair of field-aligned currents using several models of the distribution of the conductivity. Although the distribution was simpler than that used in our calculation, their results showed the greater magnitude of the current vortex in the duskside in comparison with the dawn one. The asymmetry is, therefore, not probably ascribed to the model of the conductivities. This is supported by the fact that the asymmetry in the dayside DP2 ionospheric current is well reproduced by our model of conductivities.

Another possible reason for the disagreement is that the assumption of the stationary current system, on which the calculation was based, is invalid for the simulation of the PI-associated currents. While the DP2 has a time scale with one hour and the assumption can be applied for the DP2, such a treatment is probably inappropriate for the PI because of the shorter duration. This conclusion is lead only from the rejection of one of those two possibilities, and we have no theoretical idea how the disagreement is made by any time-dependent process. At present, only the following suggestion on the unknown process will be possible.

The magnetic variation of PI observed on the Earth originates from the dusk-to-dawn electric field produced in the magnetospheric process. The Alfven wave, which carries the electric field and field-aligned current, is generated in the magnetosphere and propagated down to the ionosphere along geomagnetic lines of force. After the arrival of the wave-front at the high-latitude ionosphere, the electric field is then spread horizontally and produces the magnetic disturbances in the lower latitudes. Though, in our calculation, the current pattern produced by the horizontal transmission process is simulated by the stationary model, it is appropriate only if the process is completed enough rapidly within the time scale of the PI.

As a mechanism of the horizontal propagation of the electric field incident in high latitudes, Kikuchi and Araki (1979) proposed a propagation mode of electromagnetic wave (transverse-magnetic mode) through the Earth-ionosphere waveguide. The propagation theory ensures the instantaneous transmission of the high-latitude electric field to the equator. The duration of PI, about one minute, is considerably long enough to accomplish the transmission process of the electromagnetic wave because the mode propagation proceeds with the velocity of light. In that case, the PI in low latitudes could be simulated by the stationary current system driven by the electric field in the magnetosphere.

However, if the result of the analysis here suggests that the assumption of the stationary current system is inappropriate for the low-latitude PI, the transmission theory should be modified to include other physical processes which transmit horizontally the electromagnetic field of PI with slower velocity than that of light. Further studies are needed to understand how the high-latitude electromagnetic field is propagated toward the low latitudes.
5. Conclusions

Occurrence frequency of PI of SC observed in middle (FRD) and low (SJG) latitudes was statistically studied including the effect of the seasons and of the solar activity. To be compared with the results, the local-time variations of the amplitude of PI are numerically simulated on the assumption of the stationary state.

1. In the daytime, positive PI predominantly occurs before noon and negative PI in the afternoon. These features, which are the same as those of high-latitude PI, indicate that high-latitude ionospheric currents responsible for PI extend toward middle and low latitudes.

2. Most of PIs detected in the nighttime is negative at FRD though the occurrence rate is much smaller than in the daytime.

3. The diurnal variation in the occurrence rates of PI shows a drastic seasonal change at SJG, which is probably caused by a seasonal variation of the ionosphere.

4. Positive correlation between the occurrence rates and the solar activity was not found at either observatories in contrast with the clear correlation in the equatorial region reported by previous workers.

5. Although the symmetric distribution of the field-aligned currents with respect to the noon-midnight meridian has been used, the calculated diurnal variation of magnetic field exhibits a severe deflection from the symmetry in middle and low latitudes.

The geomagnetic data used in the present study were obtained through the World Data Center C2 for Geomagnetism, Kyoto, and the data processing was performed using facilities at the Data Processing Center at Kyoto University.

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