Electromagnetic induction due to SSC at equatorial electrojet stations

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1 Introduction

The quiet-day solar daily variationSq, of geomagnetic field has been attributed to currents in the ionospheric E-region. These currents are due to the electric field generated by the thermal and/or gravitational tidal winds acting across the vertical component of the main geomagnetic field. The enhancement of the daily variation of the horizontal field H, vertical (Z) and eastward (Y) geomagnetic fields at the five equatorial electrojet stations operating during IGY-IGC period have been discussed. The amplitude of SSC (H) at any of the stations was maximum around midday hours. The amplitude of SSC (Z) showed an abnormally large positive value at Trivandrum, the ratio ΔZ/ΔH exceeding 1.0 at any time of the day or night. These phenomena are discussed in terms of the currents in the ionosphere/magnetosphere and their induced effects in subsurface conducting layers. The most promising source for large SSC effects in Z at Trivandrum seems to be due to the concentration of normal induced currents over a wide latitude zone north and south of the magnetic equator through the conducting graben in the Palk Strait, besides the channeling of induced ocean currents in the Bay of Bengal and Indian Ocean physically through the Palk Strait between India and Sri Lanka.

1.1 Quiet day solar daily variation

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as well as by the transmission of magnetopause electric field through the polar region to the equator, intensifying the amplitude of SSC(H) within a narrow latitudes over the magnetic equator.

An increase of equatorial electric field during SSC should be associated with the increase of the electrojet current, resulting in an increase of ΔH at stations close to the equator and a decrease of ΔZ at stations near the northern periphery of the electrojet belt. A study of the SSC events at Indian geomagnetic stations Trivandrum (TRD), Kodaikanal (KOD), Annamalainagar (ANN) and Alibag (ABG) showed an enhancement of ΔH during the daytime, but the SSC effects on Z field too was a positive impulse at electrojet stations north of the magnetic equator, i.e. at KOD and ANN. An abnormally large positive impulse in Z exceeding the corresponding impulse in H was noticed at TRD, a station very close to the equator. This is an unexpected result, when ΔZ exceeded ΔH during SSC and has not been reported at any equatorial or low and midlatitude station.

In this paper, the study of the amplitude of SSC in H, Y and Z field at stations within the electrojet belt has been described for the year 1958. The stations chosen are Huancayo (HUA) in American longitudes, Addis-Ababa (AAE) in east African longitudes, TRD in India and Koror (KOR) and Jarvis (JAR) in Pacific longitudes. Some other stations' data could not be utilized due to non-availability of the magnetogram films, or due to the poor quality and insufficient series of magnetograms at the stations. The coordinates of the stations are given in Table. 1 and the location of stations are shown in the map (Fig. 1). It is to be noted that Huancayo is about 1°N, while other stations are less than one degree away from the magnetic equator.

2 Results

First of all, the yearly mean solar quiet day variations of H, Y and Z fields at each of these stations are examined. In Fig. 2 are shown the solar quiet day variations of horizontal (H), eastward (Y) and vertical (Z) fields at these stations averaged over the year 1958. At any station close to the magnetic equator, the ionospheric current would not produce any change in Y and Z components, and ΔH would have a maximum shortly before noon. These variations are definitely modified by currents induced in conducting layers inside the earth or in ocean or by spatial distribution of the electrojet current itself. It is seen from the diagram that the daily variations at Addis Ababa are close to the classical expectations, except for the large negative excursion of ΔH in the early morning hours. At Huancayo, ΔH shows well-known extraor-

<table>
<thead>
<tr>
<th>Station</th>
<th>Geogr.</th>
<th>Geomagn.</th>
<th>H nT</th>
<th>Y nT</th>
<th>Z nT</th>
<th>Dip.lat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huancayo (HUA)</td>
<td>12.1°S</td>
<td>75.3°W</td>
<td>0.8°S</td>
<td>355.2</td>
<td>27225</td>
<td>985</td>
</tr>
<tr>
<td>Addis-Ababa (AAE)</td>
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<td>38.8°E</td>
<td>5.2°N</td>
<td>110.5</td>
<td>36075</td>
<td>407</td>
</tr>
<tr>
<td>Trivandrum (TRD)</td>
<td>8.5°N</td>
<td>77.0°E</td>
<td>1.1°S</td>
<td>147.8</td>
<td>39896</td>
<td>232</td>
</tr>
<tr>
<td>Koror (KOR)</td>
<td>7.3°N</td>
<td>134.5°E</td>
<td>3.0°S</td>
<td>204.7</td>
<td>37959</td>
<td>404</td>
</tr>
<tr>
<td>Kodaikanal (KOD)</td>
<td>10.2°N</td>
<td>77.5°E</td>
<td>0.6°S</td>
<td>148.4</td>
<td>39265</td>
<td>2444</td>
</tr>
<tr>
<td>Annamalainagar (ANN)</td>
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<td>79.7°E</td>
<td>1.5°N</td>
<td>159.7</td>
<td>40309</td>
<td>4213</td>
</tr>
<tr>
<td>Alibag (ABG)</td>
<td>18.6°N</td>
<td>72.9°E</td>
<td>9.4°N</td>
<td>144.9</td>
<td>38282</td>
<td>17576</td>
</tr>
<tr>
<td>Jarvis (JAR)</td>
<td>0.4°N</td>
<td>160.1°W</td>
<td>0.3°S</td>
<td>270.4</td>
<td>34462</td>
<td>5629</td>
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</table>
ordinarily large amplitude, but $\Delta H$ is seen to start increasing since hours well before the sunrise. The $\Delta Z$ shows a minimum in afternoon hours and can be recognized, as Huancayo is 1°N of the equator. The large positive excursion of $\Delta Y$ is definitely anomalous and is the characteristic of that longitude sector only\cite{12}. At Koror and Trivandrum, $\Delta Y$ shows a significant minimum around midday; but the forenoon maximum and afternoon minimum of $\Delta Z$ are definitely anomalous features which seem to be associated with some features of the currents induced inside the solid earth.

The ratio of daily ranges in $Y$ and $H$, i.e. $\Delta Y/\Delta H$ was around 0.15 at KOR, TRD and AAE, but it was as large as 0.24 at Huancayo. The ratio $\Delta Z/\Delta H$ was smallest at AAE being only 0.07, it was 0.20 at HUA, 0.27 at KOR and 0.36 at TRD. Thus, Trivandrum seems to have extraordinarily large $\Delta Z$ in spite of its being very close to the equator.

Next, the signatures of SSC on $H$, $Y$ and $Z$ fields at these stations are illustrated in Fig. 3. It may be mentioned that the sensitivities of these traces are very different from one station to another and the impulses cannot be compared by their linear dimensions in the diagram.

At Huancayo, analogous to large $Sq(H)$ variation, the amplitude of $SSC(H)$ was also abnormally large, being 245 nT for the event shown here. The amplitude of $SSC$ in $Y$ is also large, being 40 nT in this case. It may be noted that the sensitivity of $D$-magnetometers at Huancayo is very small and the excursions of $D$ appear small. The $SSC(Z)$ is positive even though the $Sq(Z)$ at Huancayo is negative during the daytime.

At Addis-Ababa, the SSC at 1103 hrs LT on 15 July 1959 produced the excursion of 127 nT in $H$ and $-26$ nT in $Z$, while the excursion on $Y$ was slow and uncertain. It is to be noted that even during the early phases of the storm, the fluctuations in $H$ and $Z$ are of opposite sense.

At Trivandrum, the SSC at 1159 hrs LT on 5 Dec. 1958 produced an excursion of 88 nT in $H$ and even larger excursion of 100 nT in $Z$ field. The excursion in $Y$ field was as small as 7 nT only.

At Koror, the storm at 1203 hrs LT on 29 July 1958 had produced large excursions in all the three components $H$, $Y$ and $Z$.

At Jarvis, the SSC at 1626 hrs LT on 21 Aug. 1958 had produced $\Delta H$ of 84 nT and $\Delta Z$ of only 13 nT.

Thus, one finds the anomalies of SSC large in $Y$ at
Huancayo, large in Z but small in H at Trivandrum and large in H, Y and Z at Koror.

In Fig. 4 are shown mass plots of the amplitudes of SSC in H, Y and Z fields at these stations against local time for all the events during 1958-59. For Jarvis, we had magnetograms for 1958 only.

At Huancayo, SSC(H) shows well known daytime enhancement. The amplitudes of SSC(Y) range from -10 to +30 nT with a doubtful amplification during the daytime hours. The amplitudes of SSC(Z) vary between 0 and +20 nT with no variation with the time of the day. The ratio ΔZ/ΔH varied between 0.2 and 0.4 with slightly lower values during the day than during night. The yearly average value of the amplitude ratio of Sq(Y)/Sq(H) was 0.24 and that of Sq(Z)/Sq(H) was 0.20 for 1958.

At Addis-Ababa, SSC(H) shows daytime enhancement and the individual amplitudes are comparable to those at Huancayo. The SSC(Y) varied between 0 and 30 nT with no apparent variation with solar time. The amplitude of SSC in Z varied from 0 to -40 nT with the largest impulses occurring around midday hours corresponding to large impulses in ΔH. The ratio ΔZ/ΔH varied between -0.1 and -0.4 with no apparent variation on local time. The average value of the amplitude ratio of Sq(Y)/Sq(H) was 0.15, while Sq(Z)/Sq(H) was 0.07.

At Trivandrum the amplitude of SSC(H) did show daytime enhancement, but few large SSC(H) had occurred during local nighttime hours. The individual values of ΔH are smallest as compared to those at any other equatorial stations. The amplitudes of ΔY are small lying between 0 and 10 nT with no variation on local time. The amplitudes of SSC(Z) are exceptionally large and duplicating the corresponding variations of SSC(H). The ratio ΔZ/ΔH is generally larger than 1.0, reaching a value of 1.4 in some cases. The ratio of yearly average amplitudes of Sq(Y)/Sq(H) was 0.14 and that of Sq(Z)/Sq(H) was 0.36.

At Koror, SSC(H) showed usual enhancement around midday. The amplitudes of SSC(Y) were very small at any time of the day. The amplitude of SSC(Z) varied from 10 to 80 nT with a definite enhancement around midday hours. The ratio ΔZ/ΔH varied from 0.3 to 0.9. The yearly average ratio of the amplitude of Sq(Y)/Sq(H) was 0.15 and that of Sq(Z)/Sq(H) was 0.27.
At Jarvis SSC(H) did show enhancement around midday, but the amplitudes of SSC impulses in $Y$ and $Z$ were small. The $\Delta Z/\Delta H$ values were small around 0.2 only.

Addis-Ababa (AAE) and Trivandrum (TRD) are separated by only 37.3° in geomagnetic longitudes, and hence, the signatures of SSC component produced by magnetospheric currents should not differ very much, unless modified by local abnormalities in the ionosphere or subsurface conducting layers. In Fig. 5 are shown the mass plot of individual amplitudes of SSC in $H$, $Y$ and $Z$ fields at Addis-Ababa and Trivandrum against UT. It is seen that between 0700 and 1800 hrs UT the SSC(H) is consistently larger at AAE than at TRD. This suggests a decrease of SSC(H) at Indian electrojet station, probably due to electromagnetic induction in the earth's crust. The amplitudes of SSC(Y) are, in each case, of opposite sign at the two stations and the modulus value is larger at TRD than at AAE. The amplitudes of SSC in $Z$ are negative at AAE and positive at TRD. Again the modulus values of SSC in $Z$ is much larger at TRD than at AAE for anytime of the day or night. These differences in the signature of the SSCs at AAE and TRD cannot be due to the source in the ionosphere or in the magnetosphere and have to be due to regional anomalies in the subsurface conductivity of the earth.

In order to find if the abnormal $\Delta Z$ (SSC) at Trivandrum is the characteristic of the station or of Indian longitude sector, the ratio of $\Delta Z/\Delta H$ during SSC has been examined at all the geomagnetic stations in India during IGY, e.g. Trivandrum (TRD), Kodaikanal (KOD), Annamalainagar (ANN) and Alibag (ABG). It may be mentioned that Trivandrum is a coastal station almost at the centre of the electrojet belt, experiencing the largest daily range of $H$ field in India. Kodaikanal is an inland station only 2° N of the magnetic equator and experiences high positive daily range of $H$ and high negative daily range of $Z$ field. Annamalainagar is situated close to the edge of electrojet belt and experiences largest daily range (negative) of $Z$ field. Alibag is outside the electrojet belt and experiences moderate $\Delta H$ and low $\Delta Z$. In Fig. 6 one sees that the ratios of $\Delta Z/\Delta H$ due to SSCs at TRD were around 1.3-1.5 during midnight and around 0.8-1.1 during the midday hours with the whole day mean.
value of 1.17. At other equatorial electrojet stations KOD and ANN, $\Delta Z/\Delta H$ values were large and positive with a maximum around midnight and with whole day mean value of 0.36-0.38. At Alibag the signatures of SSCs were always negative for $Z$ field and the ratio $\Delta Z/\Delta H$ did not show any variation with the time of the day. Thus, the abnormality in $SSC(Z)$ seems to be experienced at all the electrojet stations in India with largest value at Trivandrum.

3 Discussion
Chapman$^7$ gave the first model of the equatorial electrojet describing the equations to compute the latitudinal variations of surface magnetic field $H$ and $Z$ due to the electrojet as a function of height ($h$) and semi width ($w$) and distance from the magnetic equator ($x$) as follows.

$$H = \frac{C}{w} \tan^{-1} \frac{2wh}{h^2 + x^2 - w^2} \quad \cdots (1)$$

$$Z = \frac{C}{2w} \log \frac{(x+w)^2 + h^2}{(x-w)^2 + h^2} \quad \cdots (2)$$

where, $C$ is the uniform electrojet current.

According to Eqs. (1) and (2), $\Delta H$ is maximum at the centre of the electrojet belt and $\Delta Z$ is maximum (negative or positive) at the (northern or southern) peripheral region of the electrojet belt. The induced currents would be in the direction opposite to the source current. If the conductivity of the earth is as-
sumed to be infinite below a depth $d$ the surface magnetic field effects can be calculated using the same equations, assuming the inducing current to be at a height of $h + 2d$.

Using the data from a close chain of observatories lying between $\pm 5^\circ$ of dip equator in the Ethiopian region, Carlo et al.\textsuperscript{13} separated the external and internal parts of total magnetic field components. It was found that the average induced effects as measured from the ratio of internal to external component ($H_i/H_e$) was pronounced for substorm ($H_i/H_e = 0.35$) rather than for $Sq$ variations ($H_i/H_e = 0.28$). Figure 7 shows the latitudinal variation of surface magnetic fields $H$ and $Z$ as a function of dip latitude for the internal and external components of the electrojet and planetary parts of the total ionospheric current during the substorm event between 0936 and 1030 hrs UT on 9 Apr. 1971. As far as the horizontal field $H$ is concerned, the effects due to the source as well as induced currents are of the same sign, adding them up to give the total observed effect with the maximum over the magnetic equator. The ratio of internal to external effects in $H$, i.e. ($\Delta H/\Delta H_e$) was about 0.39 for the electrojet component and about 0.45 for the total current. The effects on the $Z$ field were opposite for the source and the induced current. In the northern latitudes, external current produced a minimum at about $3^\circ$ and the internal current produced a maximum at the same latitudes. The total $\Delta Z$ was a reduced minimum at northern latitudes for either the electrojet or planetary or for total components of the current effects $\Delta Z/\Delta H_e$ and was about 0.29 for the total current. Thus, the basic effects of the induction of the electrojet current are an increase of surface $\Delta H$ at the magnetic equator and a decrease of $\Delta Z$ maximum or minimum at the peripheral regions of the electrojet.

Yacob and Khanna\textsuperscript{14} showed that both the daily range of $H$ and $Z$ fields at Indian observatories during IGY were largest at station closest to the magnetic equator. The value of $Sq(Z)$ was found to be 58 nT at TRD, 54 at ANN and $-46$ nT at ABG. The largest amplitude of $Z$ occurred at around 1000 hrs LT at TRD and at around 1130 hrs LT at ABG. Srivastava

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**Fig. 7**—Surface magnetic field variations of the external and internal parts of the planetary and electrojet components together with total magnetic field components ($H$ and $Z$) as a function of dip latitude for substorm event from 0936 hrs UT to 1030 hrs UT on 9 Apr. 1971 (after Carlo et al.\textsuperscript{13}).
and Sankararayan suggested the anomaly in $\Delta Z$ at Trivandrum to be due to the coastal effects and due to sub-surface conductivity anomalies. However, no comparison was made between the observations and any sort of computations.

Gettmy showed that $\Delta Z$ at Koror was positive at the time of maximum $\Delta H$. Knapp and Gettmy showed that the daily variation of $H$ field simulated the time derivative of the $H$ curve. Fukushima suggested the effect as due to induced currents at the sea surface under the development and decay of the overhead electrojet current.

Definitely the closest chains of equatorial observatories in India was operated during the International Equatorial Electrojet Year (IEEY). Numbers of temporary observatories were established besides the permanent ones. Arora et al. have described preliminary results of Indian IEEY geomagnetic projects.

Figure 8 is a modified version of one of the figures in their paper. It shows the dip latitudinal variation of the $Sq$ range of $H$ and $Z$ fields as well as of the ratio of $\Delta Z/\Delta H$.

It is clear from the variation of the $H$ field that the equatorial electrojet is superimposed over the global current system. This is in conformity with the suggestion by Rastogi. It is interesting to note that the $\Delta H$ over the equator due to total current was 125 nT, out of which the global current component was only 57 nT and hence the electrojet component was 68 nT which was greater than the global current component. Rastogi has shown, from ionospheric drift measurements at Thumba and the geomagnetic $H$ field at Trivandrum, that the total ionospheric current over the magnetic equator is composed of a planetary component of the eastward current flowing at an altitude of 107 km together with the equatorial electrojet component flowing, at an altitude of 100 km, either eastward or westward. At surface, this could result in strong electrojet, partial counter electrojet or a full counter electrojet depending upon the relative strengths and directions of the two current components.

The latitudinal variation of the range of $Z$ shows expected minimum around 3° dip latitude at Koror (KOR) and Annamalainagar (ANN). But the large positive $\Delta Z$ at lower latitude station is anomalous at Kanyakumari (KAN), Trivandrum (TRD) and Ettayapuram (ETT). It is to be noted that $\Delta Z/\Delta H$ is about 0.3 both at TRD and ANN. Thus, induced anomalous effect on $\Delta Z$ due to the daily variation is only about 30% of the $Sq(H)$ similar to the results shown in Fig. 2.

Computations were made of surface effect in $H$ and $Z$ fields due to electrojet of varying thickness and due to induced currents with varying depth of the conductor. The equatorial electrojet height is assumed to be 100 km and the conductivity of the conductor is assumed to be infinite.

The latitudinal variations of $H_0$, $H_0/H_0$ and $Z_0/H_0$ due to the electrojet having semi-thickness of 200, 300 and 400 km are shown in Fig. 9(a). Increase of the thickness results in an increase of magnitude of $\Delta H$ at the equator, i.e. $H_0$ and a greater distance from the equator being affected by the current. Examining the curves for $H_0/H_0$, one can notice that at the peripheral region of the electrojet the $\Delta H_0$ reduces to half.
the value at the equator (\(H_o\)). Increasing of semi-thickness increases the magnitude as well as range of distance for effect on \(\Delta Z\). The minimum of \(\Delta Z\) occurs at a distance equal to the semi-thickness of the electrojet.

In Fig. 9 (b) are shown latitudinal variations of \(H_x\), \(H_x/H_o\) and \(Z_x/H_o\) due to an electrojet current of semi-width 300 km flowing at an altitude of 100 km.

Regarding the induction effects, decreasing of the depth of conductor increases the equatorial value of \(\Delta H\). The \(H_x/H_o\) versus equatorial distance curve gets flatter with the increasing of depth of conductor.

Regarding \(Z_x/H_o\), the magnitude of the maximum \(\Delta Z\) increases with the decreasing depth of conductor. With the conductor almost at surface level, \(\Delta Z\) reaches the largest value of 0.7 times \(H_o\). Thus, it can be seen that no combination of the depth of conductor can produce any positive \(\Delta Z\) at the equator.

Rajaram et al.\(^2\) postulated the channelling of the internal currents through a conductor in the upper mantle or in the lower crust between India and Sri Lanka. Rajaram et al.\(^2\) estimated the depth of the subsurface conductor to be 522 km for SC storms. It can be seen from Fig. 9 (b) that even if the induced current is assumed to be in south of India and assumed to be at zero depth, even then \(\Delta Z\) would increase to a value of only about 0.7 times \(H_o\). It is not possible to get a value of \(\Delta Z/\Delta H\) equal to 1.2 as observed and definitely not so with a deep-seated conductor at 500 km below the surface.

Srivastava and Abbas\(^2\) suggested the anomalies in SSC amplitudes at equatorial stations in India due to (i) the concentration of oceanic induced currents along the coastline, (ii) its flow southward along the east coast and (iii) its concentration, as they pass through the Palk Strait.

During nighttime, there is no electrojet, i.e. ionospheric currents are too weak to be detected. The
source field producing SCs are distant and uniform. The increase of the $\Delta Z/\Delta H$ ratio at equatorial stations and the decrease of the ratio with increasing distance from the equator may be due to the diversion of induced current from non-equatorial latitudes and its concentration in the conducting channel between India and Sri Lanka.

The low value of $\Delta Z/\Delta H$ during the midday hours is due to off-setting effect of the electrojet when large induced positive effect is seen in $\Delta H$.

In Fig. 10 are reproduced the $H$ and $Z$ traces of the magnetogram at Trivandrum on 19 Mar. 1980 when a SSC was recorded at 1118 hrs LT. This event was rather a rare example when large preliminary reversed impulses were recorded in $H$ as well as in $Z$ traces before the main impulse. It is seen that the $\Delta Z/\Delta H$ for the main impulse was 0.89 and for the preliminary impulse it was 0.84. It can also be noted that following the SSC, micropulsations were observed in which the individual impulse in $Z$ was almost of the same amplitude as the corresponding impulse in $H$.

4 Conclusions

The subsurface induction effects in the equatorial electrojet currents in Indian longitude (75°E) sector seem to be a very complex phenomenon having number of different mechanisms. The most plausible source seems to be the concentration of the induced currents over a very large latitude sector through the conducting graben in the Palk Strait, thereby generating a strong band of subsurface westward current belt south of the dip equator in the region. A more quantitative study of the induction effects to decipher this complex phenomenon is required. Any geomagnetic observations south of Palk Strait, i.e. in Sri Lanka would be of tremendous help in understanding the phenomenon.

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References

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