Effects of ionospheric, magnetospheric and induced current on equatorial electrojet over India

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The paper describes the diurnal and latitudinal variations of the horizontal (H), eastward (Y) and vertical (Z) components of the geomagnetic field at Central African, East Brazilian and Indian sectors based on the chain of magnetic observatories operated in these areas. The observations in Brazilian and African sectors conform fairly well with the expectations of Chapman’s theory of equatorial electrojet. In Indian longitudes the latitudinal variation of ΔZ shows a large maximum simultaneously with the peak of ΔH over the dip equator. The daily variation of ΔZ shows a peak around 0900 hrs LT when the rate of increase of ΔH with time is largest. The peak of ΔZ is largest at Kanyakumari and decreases with increasing latitude of the station. The phenomenon is suggested due to sub-surface induction in southern Indian region and not confined to Palk Street. Solar flares cause a temporary increase of the ionospheric current along the pre-flare direction. Faster flares indicate induction effects at each of the equatorial stations. The storm time variation of Z also shows the sub-surface induction effects at electrojet stations in India. Storm time variations in H are shown to be enhanced over the stations close to the dip equator during the local mid-day hours. The equatorial electrojet is shown to be closely affected by ionospheric as well as magnetospheric currents and by the currents induced by these in sub-surface conducting regions.

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1 Introduction

A standard geomagnetic observatory had been operating at Kodaikanal, a station close to the magnetic equator in India since 1902. However, the establishment of a geomagnetic observatory at the equatorial station Huancayo in Peru in 1922 showed an abnormally large solar daily range of H field larger than that at any other station in the world. McNish tried to modify the Stewart theory to take into account the southern displacement of the magnetic equator in that longitude sector. The current must flow generally against the induced electromotive force, but he found that in western hemisphere the current can pass around the entire circuit without encountering unfavourable electromotive force. Chapman found that the solar daily range of H at stations in Uganda, lying between the geographic and magnetic equators, was as large as that at Huancayo. However, the measurements at Mombasa and Singapore did not show abnormal variations of S(H). He concluded that the large S-range in H is not strictly confined to inter-equatorial belt. Martyn suggested a region of high electric conductivity encircling the world, approximately, midway between the magnetic and geomagnetic equators.

Chakarbarty showed that the solar quiet-day variation curves of the horizontal magnetic field H at low but equal geographic latitudes, differ widely both in intensity and type and suggested a geomagnetic control of $S_z H$ variations for low latitude stations although for high latitude stations, it is more dependent on geographic coordinates. It is not understood why the observations at equatorial station Kodaikanal and Madras were not used for comparison with those at other longitudes. Egedal used the magnetic data from Indian stations Kodaikanal, Madras and Alibag together with those from Antipolo, Batavia and Huancayo. He plotted the range of H against the magnetic inclination and discovered a great augmentation of the range of H in a narrow zone near the magnetic equator. Chapman interpreted this as due to a band of intense current flowing eastward during the daytime hours centred over the dip equator and named it normal equatorial electrojet (NEJ) current.

Chapman gave the first model of the equatorial electrojet. Considering the field due to an infinitely long straight eastward current of total strength C emu, he showed that the intensity at a distance r from the axis is $2C/r$. If the current is flowing horizontally at a...
height $h$ above the surface, then at distance $x$ to the south, the horizontal component $H$ due to the current is $2C_h/(x^2 + h^2)$ and the downward vertical component $Z$ is $2C_v/(x^2 + h^2)$. If the electrojet is represented by a “band” current of width $2w$ at a height $h$ then simple integration gives that at a distance $x$ south of the axis of the band current

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

and

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

The value of $H$ at the centre of the electrojet belt ($x = 0$) is $H_0 = 2C/h$. Then elsewhere

$$H_x = H_0 \frac{h^2}{x^2 + h^2} \quad \ldots(3)$$

and

$$Z_x = H_0 \frac{xh}{x^2 + h^2} \quad \ldots(4)$$

The horizontal component $H$ has its peak directly under the current, falls away to one-tenth $H_0$ at $x/h = \pm 3$, and $Z_x$ has its maximum (or minimum) value equal to 0.67 $H_0$ at a distance $x = w$. With these relations between $\Delta H$ and $\Delta Z$ with $x$, the parameters of the electrojet current, its height, width and intensity have been inferred by a number of workers\textsuperscript{7-9}.

Chapman\textsuperscript{6} had computed the latitudinal variations of $\Delta H$ and $\Delta Z$ fields due to a thin band of the current. In Fig. 1 are shown the latitudinal variations of $\Delta H$ and $\Delta Z$ due to a current flowing at 105 km within the dip latitudes $\pm 3^\circ$. At the edge of the electrojet belt, $\Delta H$ is reduced to 0.56 times the value over the equator ($\Delta H_0$). The $\Delta Z$ is maximum at the latitudes close to the edge of the electrojet, this value ($\Delta Z_m$) is 0.67 times $H_0$. Thus, near the edge of the electrojet belt, $AZ$ would be larger than $\Delta H$ if the effect is entirely due to the ionospheric current. The ratio of $\Delta Z/\Delta H$ is zero at the equator and increases rapidly with latitude. Various models using different vertical cross-sections of the electrojet have been described by many workers\textsuperscript{10-12}. However, no major deviations from Chapman’s model were noted in ground magnetic field variations.

Soon after the discovery of the equatorial electrojet, the Association of Terrestrial Magnetism and Atmospheric Electricity organized a committee under the chairmanship of J Egedal to promote observations of daily variations of horizontal magnetic force between and near the geographic and geomagnetic equators. Gulatee\textsuperscript{13} organized the measurement of the diurnal variation of $H$ at five places in Southern India and Ceylon. Pramanik and Yegna Narayan\textsuperscript{14} described their measurement of the daily variations of $H$ and $Z$ at three places in South India. Maximum $\Delta H$ were observed at Mandapam (Geogr. lat., 9.3$^\circ$N) and the ratio of $\Delta H$ with respect to that at Kodaikanal was 1.21. Their observations\textsuperscript{14} are plotted in Fig. 2. The daily range of $H$ field was maximum about one hour before noon at any of the stations; the values of range $H$ were 155 nT at Cape Camorin (Inclination $I = 0.9^\circ$S), Palamcottah ($I = 0.1^\circ$S) and Sankaranainakoil ($I = 0.4^\circ$N) based on the observations by Pramanik and Yegna Narayan\textsuperscript{14}.

![Fig. 1 — Latitudinal profile of $H$ and $Z$ produced by a thin equatorial electrojet current flowing at an altitude of 105 km within dip latitudes 3$^\circ$N-3$^\circ$S, computed according to the Chapman model of the equatorial electrojet (after Chapman\textsuperscript{6})](image1)

![Fig. 2 — Daily variations of $H$ and $Z$ at three equatorial stations Cape Camorin (Inclination $I = 0.9^\circ$S), Palamcottah ($I = 0.1^\circ$S) and Sankaranainakoil ($I = 0.4^\circ$N) based on the observations by Pramanik and Yegna Narayan\textsuperscript{14}](image2)
Camorin (inclination $I = 0.94^\circ$S), 130 nT at Palamcottah ($I = 0.06^\circ$S) and 125 nT at Sankaranarainarkoil ($I = 0.43^\circ$N). It is important to note that peak of $\Delta Z$ (= 30 nT) was observed at around 0900 hrs LT at Cape Camorin where Z should not have shown any daily variation. The forenoon peak of $\Delta Z$ was present at Palamcottah and Sankaranarainarkoil with decreasing magnitude. Additional surveys were made in Indian region during the period February-March 1953 by Pramanik and Hariharan. Their observation showed the enhancement of solar daily variations of stations north of both geographic and magnetic equators and thus, proved the invalidity of the suggestions by McNish for the abnormal current at equatorial stations in American longitudes. There were no plausible arguments to explain the equatorial enhancement in terms of corresponding increase of atmospheric tides over the magnetic equator. A proper answer for the enhanced currents over the magnetic equator were given by Baker and Martyn, who showed that the difference in the mobility of ions and electrons in the E-region over the equator in the direction normal to the magnetic and electric fields gives rise to a vertical Hall polarization electric field which further enhances the east-west electrical conductivities within $\pm 3^\circ$ latitudes over the magnetic equator. The latitudinal variations of $H$ and $Z$ at equatorial stations along limited longitude belt in Nigeria by Onwumechilli had confirmed that the observations were as expected of Chapman’s model of equatorial electrojet.

During the International Geophysical Year (IGY) (1957-58), the study of the equatorial electrojet was an important activity in a number of countries situated at low latitudes. India established equatorial electrojet geomagnetic observatories at Trivandrum (inclination, $I = 0.6^\circ$S) and at Annamalainagar ($I = 5.4^\circ$N). United States established field observatories at Koror ($I = 0.1^\circ$S), Jarvis ($I = 2.2^\circ$N) and Fanning ($I = 10.6^\circ$N). Ethiopia established a permanent observatory at Addis-Ababa ($I = 1.2^\circ$N) and Carnegie Institute of Washington and Instituto Geofísico del Peru operated field observatories at Yauca ($I = 4.6^\circ$), Chimbote ($I = 6.6^\circ$N), Chiclayo ($I = 10.6^\circ$N) and Talara ($I = 14.2^\circ$N). An observatory near the southern edge of the equatorial electrojet belt was established at Ibadan, Nigeria ($I = 8.6^\circ$S).

The first important result of IGY observation was the discovery of the longitudinal variation of the strength of the equatorial electrojet current by Rastogi. The current strength was found to be largest in American sector and weakest in Indian sector. Forbush and Casaverde published a comprehensive report of the analysis of geomagnetic data from Peruvian stations. The daily variations of $H$ and $Z$ at different stations were shown to be as expected of the band structure of the electrojet current. The latitudinal variations of $\Delta H$ and $\Delta Z$ too were as expected, the curves were symmetrical about the latitude of dip equator ($13^\circ$S). However, abnormally large amplitudes of $\Delta Z$ were observed around the southern end of the electrojet belt.

Godivier and Crenn described the results of magnetic field measurement along the meridian of 18°E from February to July 1958 at eight stations. They found that the maximum of $S_q$ ($H$) was in the morning hours at stations within 10 km north and south of the magnetic equator and at noon they join together at the magnetic equator. Similar observations are not reported anywhere so far. Latitudinal variations of $\Delta H$ and $\Delta Z$ followed as expected of band model of the electrojet.

Yacob and Khanna reported an abnormally large daily range of Z at Trivandrum in spite of its being very close to the dip equator. They suggested that the lag of a couple of hours between $S_q$ ($H$) and $S_q$ ($Z$) variations are due to the effects of N-S and S-N branches of the $S_q$ current in addition to the W-E branch. They did mention the contribution of induced currents within the earth.

Knapp and Gettmy pointed out that the $S_q$ ($Z$) at Koror simulates the time derivative of the $S_q$ ($H$) curve. They suggested that a north-south current flow at Koror is super-imposed over the conventional $S_q$ pattern of ionospheric current system during the day-light hours.

Chapman and Rajarao showed that the monthly mean quiet-day daily range of $S_q$ ($H$) and $S_q$ ($Z$) at all observatories in the equatorial electrojet region operating during the IGY indicated a seasonal variation mostly with equinoctial maxima and solstitial minima; these variations exceed the effects due to the cosine of zenith angle of the sun.

The first comprehensive study of the equatorial electrojet using multi-station data in the same longitude sector was described by Forbush and Casaverde. First they separated the observed total ranges of $H$ and $Z$ ($r_H$ and $r_Z$) into components due to normal $S_q$ variations ($r_H^N$ and $r_Z^N$) and components due to the equatorial electrojet current ($r_H^E$ and $r_Z^E$). Later, each of these ranges was separated into two
components — one due to currents of external source and the other due to currents induced inside the earth core. Their analyses showed that the ratios of internal to external part of $H$ field was 0.40 for $S_q$ component and 0.36 for the electrojet component of the total current. Their data fitted with the eastward band of current of total width 660 km and 142 amp km$^{-1}$ flowing at height 100 km. They assumed the earth to be non-conducting to a depth of 250 km and perfectly conducting at depth greater than 250 km. The latitudinal variation of the $H$ field was fairly symmetrical about the magnetic equator plane with maximum range of $H$ being 205 nT. The mean daily range of $Z$ was zero at the equator, $-44$ nT at the northern and $+93$ nT at the southern edge of the electrojet belt. Abnormally large amplitude of the daily range of $Z$ was observed at Yauca ($I = 4.4^\circ S$), but no diurnal asymmetry in $\Delta Z$ was seen at any of the stations.

Another geomagnetic survey in Peru was organized by the Carnegie Institute of Washington and Instituto Geofísico del Peru during July-September 1963. The results are described by Schmucker et al. They found a steady increase of the noon maximum in $H$ from Ayanquera, 400 km to the south of the dip equator to Cuzco right on the dip equator, demonstrating the effect of equatorial electrojet superimposed on the normal $S_q$ current. The small variations of $Z$ at the equatorial stations and the southward increasing midday $Z$ peak at the southern stations corresponded well with an overhead equatorial electrojet. It was concluded that any contribution from induced eddy currents to the observed variations were rather small. During the next geomagnetic survey from October to May 1966 some field stations were located at off-coastal regions and southward towards Bolivia. Schmucker et al. describing the results concluded the presence of internal current directed to the north as a result of high mantle conductivities under the Andes mountain chain.

The daily and latitudinal variations of $H$ and $Z$ field at any network of geomagnetic observatories on both sides of the magnetic equator and lying between a narrow longitude sector were first described by Fambitakoye based on observations at stations operated between the period July 1969-January 1970 in Central Africa. In Fig. 3 are shown the latitudinal variations of $\Delta H$ and $\Delta Z$ at each hour of the daytime (28 January 1969) spreading 1000 km on each side of the dip equator. The $\Delta H$ value is seen to be an enhancement over the global $S_q$ current above about 600 km centred with a peak over the magnetic equator. The two peaks of $\Delta Z$ are at 300 km south and north of the equator. These features confirm the expectations of the equatorial electrojet. At 0630 hrs LT the latitudinal profile of $\Delta H$ showed a minimum over the dip equator and $\Delta Z$ profile showed a maximum in northern edge and a minimum at the southern edge of the electrojet belt. These two facts indicate a counter electrojet event at that time. At 0730 hrs LT the counter electrojet effect decreased and at 0830 hrs LT, clearly normal electrojet had developed. It is suggested that in the Central African longitude sector the reversal of the atmospheric dynamo electric field in the dawn hours occurs significantly after the sunrise when significant increase of E-region ionization has been formed. The increase of maximum ionization in the E-layer of the ionosphere, $N_mE$, with the existing nighttime condition of electric field causes a westward current indicated by counter electrojet. No such phenomenon was observed during dusk hours.

The ratio of minimum $Z$ near the edge of the electrojet belt ($\Delta Z_m$) and the $\Delta H$ value at the centre of the electrojet belt ($\Delta Z_m/H_0$) is also indicated in the diagram. The value near midday hours was around 0.65, which is close to the theoretically computed
value of 0.67. But it is not understood clearly why the ratio was about 0.50 in the morning and increased steadily to above 0.80 by the evening.

The densest network of the magnetic observations within the equatorial electrojet belt was operated by Rigoti et al. In Fig. 4 are reproduced the latitudinal profiles of $\Delta H$ and $\Delta Z$ for each hour of 6 January 1996. At this longitude sector, no indication of electrojet current, eastward or westward can be seen at 0500 hrs LT. At 0600 hrs LT, $\Delta H$ is lower at magnetic dip than at other lower latitudes, and $\Delta Z$ is higher in the northern than the southern low latitudes. At 0700 hrs LT again the signs of a weak counter electrojet can be inferred from the latitudinal profiles of $\Delta H$ and $\Delta Z$. At 0800 hrs LT the latitudinal profiles of both $\Delta H$ and $\Delta Z$ are very flat, but at 0900 hrs LT very clear normal electrojet signatures are seen in $\Delta H$ and $\Delta Z$ profiles. The increase of $\Delta H$ over the equator and $\Delta Z$ at the latitudes of electrojet boundary with the development of the day and their decline in the afternoon hours can be clearly seen. No counter electrojet effects are seen at the dusk hours.

During the International Equatorial Electrojet Year, 1992-1993, some field observatories were established in India by Indian Institute of Magnetism in addition to the permanent observatories already existing. In Fig. 5 are redrawn the daily variations of $\Delta H$ and $\Delta Z$ at the regular observatories and at field stations for the five quiet days of February 1992. The daily variation of $\Delta H$ at different stations was as expected of the Chapman model of equatorial electrojet, being maximum at stations closest to the magnetic equator and progressively decreasing with increasing latitude of the station. The daily variations of $\Delta Z$ at stations south of magnetic equator were different from the expectations of Chapman’s model. The forenoon (0930 hrs LT) anomaly peak of $Z$ was stronger at Kanyakumari, KAN, ($I = 0.6^\circ$S), a field station south of the permanent observatory at Trivandrum, TRD, ($I = 0.6^\circ$N). The peak of $\Delta Z$ decreased at Ettayipuram, ETT, ($I = 2.1^\circ$N), a station north of Trivandrum and the daily variation of $\Delta Z$ becomes uncertain at a more northerly station Virudhnagar, VIR. At Kodaikanal, KOD, ($I = 4.7^\circ$N) the midday decrease of $\Delta Z$ was quite clear, the characteristic of a station near the northern edge of the equatorial electrojet belt. At Karur, KAR, and Annamalainagar, ANN ($I = 7.3^\circ$N), the midday depression is still stronger, but it decreased at a further northerly stations Bangalore ($I = 17.1^\circ$N). Thus, apparently the equatorial stations

![Fig. 4](image1.png)

![Fig. 5](image2.png)
KAN, TRD, ETT seem to be affected by anomalous induction effect, while KOD, KAR and ANN situated near the northern edge of the electrojet belt are affected primarily by the ionospheric current only. It is also to be noticed that the forenoon peak of $Z$ at KAN occurred after 0930 hrs LT, at TRD it was at 0900 hrs LT, at ETT it was at 0830 hrs LT and at VIR probably at 0730 hrs LT and was absent at KOD. Similarly, the midday dip was at 1130 hrs LT at KOD, at VIR at 1430 hrs LT, at ETT at 1630 hrs LT and at TRD and KAN at 1830 hrs LT. It seems that the induction effects start immediately after the start of electrojet and progressively get stronger and delayed in time at stations nearer to the equator. The observed induction effects in $S_q (Z)$ at any of the stations are the combined effects of direct ionospheric and induced currents, and the two currents have significant phase differences.

In Fig. 6 are shown the development of the latitudinal profiles of $\Delta H$ and $\Delta Z$ at different hours of the day at Indian longitude stations during February 1992. The equatorial peak of $\Delta H$ was very feeble before 0830 hrs LT. At 0830 hrs LT the equatorial peak $\Delta H$ was about 63 nT and that of $\Delta Z$ was +32 nT at KAN and −10 nT at ANN. At 0930 hrs LT, $\Delta Z$ increased to +45 nT at KAN and decreased to −25 nT at ANN. At 1130 hrs LT, the decrease of $\Delta Z$ at ANN was largest being equal to −37 nT, but $\Delta Z$ at KAN was reduced to +35 nT.

To compare the observed minimum $\Delta Z$ near the edge of the electrojet ($\Delta Z_m$) with the $\Delta H_o$ near the centre of the electrojet, the ratio of $\Delta Z_m/\Delta H_o$ was also indicated for different hours of the day in Fig. 6. It is seen that $\Delta Z_m/\Delta H_o$ is 0.70 in the morning hours, around 0.57 at 1130 hrs LT and increased to 1.00 at 1630 hrs LT. This suggests a significant difference between the observed daily variation of $\Delta H$ and $\Delta Z$ from the Chapman’s model and need to be explained. This could be due to the changes in the distribution of current within the equatorial electrojet.

Arora et al. had analyzed the $S_q (H)$ and $S_q (Z)$ variations at Indian stations into component due to global current system and due to the electrojet current separately. Their results showed that during the midday hours, out of total $\Delta H = 124$ nT over the equator, the global current component was 58 nT and the electrojet current component was 66 nT. The $\Delta H$ at Alibag is generally taken as the representative of global current component at the time and the equatorial electrojet component of the current over the dip equator is taken as $\Delta H (TRD) – \Delta H (ABG)$. This index of electrojet current is very well related to the

![Fig. 6 — Diurnal development of the latitudinal variation of H and Z fields at the Indian stations during the month of January 1992 (after Arora et al.)](image-url)
Doppler shift of the VHF backscatter radar echoes (Rastogi and Patil\cite{28}) or with the disappearance of equatorial sporadic E-layer at Kodaikanal (Rastogi et al.\cite{29}).

Arora et al.\cite{27} had separated the electrojet part of $\Delta H$ at different stations into external (ionospheric) and internal (induction) components. The $\Delta Z$ fields, separately due to the ionospheric and due to induced current, were computed using Chapman’s model. Adding these two contributions, the estimated latitudinal variation of $\Delta Z$ was obtained. These are shown in Fig. 7. It is seen that the observed data are very close to the external part of $\Delta Z$ at latitudes near and beyond the edge of the electrojet, but depart appreciably at latitudes lower than $3^\circ$N (distance from the equator less than 300 km). Thus, the anomaly in $\Delta Z$ due to induction and estimated values of $\Delta Z$ are confined to regions nearer than 250 km from the equator, and is largest at the southernmost region of south Indian peninsula. The component $\Delta Z$ showed very large values over the equator, the ratio of $\Delta Z/\Delta H$ being almost 0.7-0.8. At 0930 hrs LT, there were more rapid increase of $\Delta H$ at equatorial electrojet stations indicating the development of electrojet current modulating the global $S_q$ current. There were no large increase of $\Delta Z$ over the equator, but $\Delta Z$ at stations near the edge of EET, KAR and ANN showed rapid decrease of $\Delta Z$. At 1030 hrs LT and 1130 hrs LT, the electrojet current shows its strongest development and $\Delta Z$ at the stations near the fringe of the electrojet belt showed further large decrease. The equatorial anomaly in $\Delta Z$ did not show any spectacular changes. After midday, the magnitudes of both positive $\Delta Z$ at equatorial stations and negative $\Delta Z$ at stations around 3-4$^\circ$ dip latitudes showed rapid decreases. By 1630 hrs LT the electrojet part of the current had almost disappeared and the $\Delta Z$ profile becomes constant with latitude. Thus, it is very clear that the development of the $S_q$ and electrojet components of the total currents and, therefore, the effects of their induced currents are not coincident with time. Rastogi and Patil\cite{28} comparing the geomagnetic $H$ data at Trivandrum and Alibag with the Doppler shifts of VHF radar at Thumba had shown that the development of the electrojet current is significantly delayed with the development of the global $S_q$ current component of the total overhead current.

Four magnetic observatories have been operating within the equatorial electrojet belt in India since January 1980. The average $S_q (H)$ and $S_q (Z)$ variations at these observatories averaged over the five years (1980-1984) as well as the time gradient of $\Delta H$ are shown in Fig. 8. As expected the magnitude of $S_q$...
range decreased progressively from TRD, ETT, KOD to ANN. The time gradient of $H$ showed a peak of $+30$ nT per hour at 0900 hrs LT and another peak of $-25$ nT per hour at 1400 hrs LT for any of the stations. The $S_Q$ at TRD showed a strong peak of $25$ nT at 1000 hrs LT and at ETT the peak was of only $+7$ nT, but at more northern stations no positive peak was seen and strong negative peaks of $-25$ nT and $-30$ nT were observed at KOD and ANN. Thus, it seems that the anomaly in $Z$ is seen clearly only at southernmost stations TRD and ETT.

In Fig. 9 are shown the yearly mean $S_Q$ variations of $H$ and $Z$ at all equatorial stations in India from Trivandrum to Alibag for the low sunspot year 1994 and for the high sunspot year, 1991.

During the low sunspot year 1994, the $H$ field started increasing at around 0600 hrs LT at EEJ stations and slightly later at other stations north of EEJ stations. The peak $\Delta H$ was about half an hour before noon. The afternoon decay of $\Delta H$ was fairly symmetrical with forenoon increase and by 1800 hrs LT the $\Delta H$ was reduced to the base value. The $\Delta Z$ showed positive peak at TRD, ETT and slightly at KOD and ANN and was practically absent at Hyderabad (HYB) and Alibag (ABG).

During high sunspot year 1991, the morning increase of $\Delta H$ started after sunrise, but afternoon decay of $\Delta H$ continued even after sunset, reaching the base level by midnight. The forenoon peak of $\Delta Z$ was evident even at the latitudes of ABG. Thus, the subsurface induction of the ionospheric current extend to larger latitudes in India during high sunspot years.

In Fig. 10 are shown the diurnal variations of $\Delta H$ and $\Delta Z$ at the three equatorial stations Trivandrum, Ettayiapuram and Kodaikanal during a counter electrojet period on 29 Jan. 1993. The $\Delta H$ curve at TRD showed a decrease of $35$ nT below the base value at 0730 hrs LT indicative of a westward electrojet current which recovered to normal $S_Q$ value by 1330 hrs LT. Correspondingly, $\Delta Z$ at TRD which shows a positive peak in forenoon hours, now showed a negative value of $-10$ nT at 0830 hrs LT and in the afternoon hours showed a positive value due to the continuation of the partial counter electrojet conditions. At Ettayiapuram and Kodaikanal too, $\Delta H$
showed a depression at around 0830 hrs LT as a result of the westward counter electrojet current. The ΔZ at these stations showed positive values throughout the day instead of the normal decrease due to the eastward ionospheric current. This further confirms that the abnormal ΔZ values at the forenoon and afternoon hours at Trivandrum are due to the effect of induction in sub-surface conductivity anomalies.

2 Electromagnetic induction due to bay events

Sometimes, nighttime magnetograms at low latitude stations show a simple slow increase or decrease of the H field, lasting for a few hours resembling typical coastline forms and are called geomagnetic bays. These events arise from a worldwide overhead current system associated with auroral disturbances. These events occur when no electrojet is present over the magnetic equator. The ionospheric currents at low latitudes may be assumed to be fairly uniform. Schmucker et al. described the geomagnetic field variations in Peru during a bay around 1910-2000 hrs LT on 23 July 1963. The H variations were seen to be considerably uniform at all stations, but a non-uniform behaviour was seen in the variations of Z.

Figure 11 shows the variations of ΔH and ΔZ at Indian stations during the bay events on 18 Jan. 1974 and 10 Feb. 1974. The variations at Addis-Ababa (AAE) are also indicated for comparison. On 18 Jan. 1974, there occurred a positive bay of amplitude of 54 nT at Trivandrum between 1700 and 1800 hrs UT or 2200 and 2300 hrs LT. All other Indian stations also recorded corresponding bay of almost same magnitude. The bay at Addis-Ababa occurred at the same time but of slightly less magnitude. It is to be noted that the deflection of Z field at Addis-Ababa was too small, the ratio of ΔZ/ΔH being only 0.2. At Trivandrum, ΔZ was 70 nT as compared to ΔH = 55 nT. The ratio of ΔZ/ΔH was 1.3. At other stations in India, farther from the magnetic equator, the ratio ΔZ/ΔH decreased and was as low as 0.2 at Hyderabad (HYB). The bay events on 10 Feb. 1974 started at 2330 hrs UT or at 0430 hrs LT. It is again seen that the ratio of ΔZ/ΔH at Addis-Ababa was very low being only 0.1, it was largest at Trivandrum being equal to 1.1 and decreased progressively with increasing distance of the station from the magnetic equator. Unlike the Sq variation, the bay associated currents do produce induction even up to the latitudes of Annamalainagar.

3 Induction effect in equatorial electrojet due to solar flares

Solar flare effects (SFEs) on geomagnetic field components observed at ground are the manifestation of a temporary increase of solar ionization radiations, ultra violet and X-ray radiations from the sun. These flares increase the ionization in the dayside of the ionosphere without disturbing the existing electric field. These, in turn, cause an increase of ionospheric current magnitude without any change of direction. The changes in H field give information of the ionospheric electric field, or of ionospheric conductivity at the time of flare initiation. The amplitude of ΔH due to solar flares is found to be enhanced over the dip equator in a manner similar to the enhancement of ΔH on quiet days. Rastogi et al. discussed SFE in H and Z fields at all Indian stations during strong and weak normal electrojet days as well as on counter electrojet days. It was shown that ΔH(SFE) on normal electrojet days consisted of positive impulse at all station. During counter electrojet days ΔH(SFE) was negative at equatorial and positive at other low latitude stations. Rastogi et al. described the effects in H, D and Z fields at stations along Indo-Russian chain due to very intense solar flare at 1311 hrs LT on 15 June 1991. It was shown that the ΔH (SFE) varied with latitude in exactly the same way as ΔH before the start of the flare. The impulses in Z field were abnormally large and positive at Trivandrum and Etthiapuram. The importance of induction in the frequency range of the flares was further strengthened when Rastogi showed that the ratio ΔZ/ΔH at Trivandrum increased
linearily with the increase of the growth rate of the SFE in $H$. For slow flares $\Delta Z/\Delta H$ was about 0.3 and the ratio for SFE with $\Delta Z/\Delta H$ at Trivandrum, equal to or less than 1.0 and the $\Delta Z/\Delta H$ (SFE) at Annamalainagar was negative. But in cases of fast SFEs when $\Delta Z/\Delta H$ at Trivandrum exceeded 1.0, $\Delta Z/\Delta H$ at Annamalainagar was also positive, a station very close to the edge of the equatorial electrojet belt. The SFE in $\Delta Z/\Delta H$ was negative when $\Delta Z/\Delta H$ (SFE) at Trivandrum is equal to or less than 1.0. But for fast flares when $\Delta Z/\Delta H$ at Trivandrum exceeded 1.0, the $\Delta Z/\Delta H$ (SFE) at Annamalainagar was also positive. In other words, the slow flare produced negative impulse in $Z$ and fast flares produced positive impulse in $Z$ at Annamalainagar. Thus, SFEs in $Z$ at Annamalainagar are the combined effects due to ionospheric and induced currents, the two being of opposite sense.

After scaling the magnetograms at all available equatorial electrojet observatories operating during the IGY-IGC for SFE in $H$, $D$ and $Z$, Rastogi$^{33}$ showed that SFE($Z$) showed abnormally large and positive value at Trivandrum. The ratio $\Delta Z/\Delta H$ due to SFE was around 0.5. At Addis-Ababa it was around 0.3. Thus, the most abnormal behaviour of SFE at electrojet stations was observed in the Indian sector.

4 Electromagnetic induction in equatorial electrojet due to SSC

Sudden storm commencements (SC) are another transient magnetic disturbances associated with the arrival of the solar plasma particles consisting the protons and electrons at the boundary of the earth’s magnetosphere, compressing it and causing a temporary sudden increase of $H$ field at all stations in the world. The magnitude of $\Delta H$ at low latitudes due to SC was shown by Rastogi et al.$^{31}$ to be enhanced over the dip equator exactly similar to the $S_q$ ($H$) amplitude itself suggesting its association with the equatorial electrojet. The $\Delta H$ due to SC at an equatorial electrojet stations was shown to be associated with increase of eastward electric field in the ionosphere$^{36,37}$.

Rastogi$^{38}$ discussed the effect of SC on $H$, $Y$ and $Z$ fields at equatorial electrojet stations operated during IGY by studying their signatures on the copies of original magnetograms. The amplitudes of SC ($H$) were maximum around local midday hours at any of the stations. The amplitude of SC($Z$) showed abnormally large positive values at Trivandrum, and $\Delta Z/\Delta H$ during SC varied from 0.3 to 0.9. At other stations $\Delta Z/\Delta H$ due to SC were small. Thus, out of all the equatorial electrojet stations, Trivandrum shows the most abnormal behaviour of $Z$ amplitudes due to SC.

5 Electromagnetic induction during magnetic storms

Following a SC, the solar wind plasma continues to compress the earth’s magnetosphere thereby increasing the $\Delta H$ at all stations above the normal quiet time value, a period called the ‘initial phase’ of the storm. A southward turning of the interplanetary magnetic field (IMF) component normal to the ecliptic (IMF- $B_z$) permits some of the solar plasma to enter the earth’s ionosphere at high latitudes which gets trapped in earth’s field lines and oscillates between high north and south latitudes. Simultaneously the protons drift westward and electrons drift eastward causing a westward current called ‘equatorial ring current’ in the magnetosphere. This generates a rapid and large decrease of the magnetic field at all stations around the world, signifying the ‘main phase’ of the storm. The magnitude of the ring current is gauged by a $D_s$ index, first suggested by Sugiuira$^{39}$. The hourly values of $D_s$ index are regularly computed and published by the World Data Centre at Kyoto, Japan. Rastogi$^{39}$ discussed the storm time variations of $H$ and $Z$ fields at magnetic observatories in India and found an abnormal decrease of $Z$ at equatorial electrojet stations Trivandrum, Ettayiapuram, Kodaikanal and Annamalainagar with decreasing magnitude of impulse. The peak decrease in $Z$ was found about three hours before the time of peak decrease of $H$, i.e. during the middle of main phase of the storm when the ring current was developing at fastest rate. This was explained as due to sub-surface conducting region where currents are induced by the magnetospheric currents.

Next, the storm time variation in $H$ and $Z$ fields at other equatorial stations around the world and at stations along Indo-Russian sector during varying conditions of ionospheric and magnetospheric currents are critically examined as follows.

In Fig. 12(a) are shown storm time variations of $H$ and $Z$ field at Koror following SC at 0124 hrs UT on 11 Feb. 1958 and another SSC at 0043 hrs UT on 7 June 1958. It can be seen that storm time variation in $Z$ is indicated by a decrease, few hours before the peak of the storm. It is interesting to note that the 7 June 1958 storm had shown very sharp decrease of $H$ by more than 300 nT, i.e. the rate was 150 nT per hour in the two hours, with the minimum at 0330 hrs UT, while the minimum $\Delta Z$ was –100 nT at 0230 hrs
During the February 1958 storm, the $H$ field had decreased by about 600 nT in eight hours between 0330 and 1130 hrs UT, i.e. the rate was only 55 nT per hour. The decrease of $Z$ field from pre-disturbed value was 100 nT with the minimum at 0730 hrs UT. Thus, it is indicated that the storm time decrease in $Z$ at Koror does not depend on the maximum decrease of $H$ field, but on the rate of decrease of the $H$ field, suggesting predominant induction effects in $Z$ field during the main phase of the magnetic storms.

In Fig. 12(b) are shown the comparisons of the storm time variations of the $Z$ field of Trivandrum and Addis-Ababa during the magnetic storms on 19 Dec. 1980, 12 Sep. 1986 and 10 May 1992. It is seen that there were significantly large decreases of $\Delta Z$ at Trivandrum, but practically no decrease of $\Delta Z$ at Addis-Ababa, even though the two stations are very close to each other for the source current at magnetospheric region. This indicates that the abnormal sub-surface conductor are very local features.

The storm time variations in the $Z$ field at Indian stations seem to be first described by Rajaram et al.\textsuperscript{40} for the storm on 21 Nov. 1975. They computed deviations of the hourly mean values of $H$ and $Z$ from the corresponding values on the $S_q$ days and plotted 13-h running mean values of these deviations against the storm time reckoned from the hour of SC. They compared the observed values against the theoretical values derived according to the method of Rikitake and Sato\textsuperscript{41}. Their diagram is reproduced in Fig. 13 on a uniform scale for $\Delta H$ and $\Delta Z$ to compare the storm time effects on the two components. It was found that the deviation of $H$ compared well with the theoretical curve. The theoretical curve for the storm time variations of $Z$ of equatorial stations, TRD, KOD and ANN on present scale of $Z$ in the diagram were indistinguishable from the zone line. Thus significant decreases of $\Delta Z$ were observed at the equatorial
stations TRD, KOD and ANN compared to the theoretical values. At other low latitude stations, a reasonable correspondence was noticed with the theoretical values. At Trivandrum, maximum $\Delta Z$ of $-20$ nT was observed at 20 h storm time, whereas the minimum $\Delta H = -70$ nT was at 24 h storm time. The magnitude of $\Delta Z$ was smaller at KOD and ANN. They attributed the results as due to electromagnetic induction in the conducting channel between India and Sri Lanka.

In Fig. 14 are shown the storm time variations of $H$ and $Z$ field at Indian stations and at Addis-Ababa following a SC at 1303 hrs LT on 15 July 1959 along with corresponding variation of $D_{st}$ index. The $D_{st}$ index shows a sudden decrease immediately after the SC and another main decrease beginning at 1830 hrs LT on 15 July, the minimum $D_{st}$ was at 2330 hrs LT (midnight of 15-16 July 1959). The storm time variations of $H$ field at other stations showed decreases similar to the corresponding decrease in $D_{st}$ index. As the storm was at local midnight, the main decrease was of the same magnitude at any of the stations. The curve for $H$ (TRD) – $H$ (ABG) shows a constant value throughout the storm period suggesting almost no equatorial electrojet current on these days. The storm time variation of $Z$ field shows large decrease at 1230 hrs LT and 2330 hrs LT on 15 July. There are similar decreases of $Z$ field at other Indian electrojet stations Kodaikanal and Annamalainagar. It is to be noted that the storm time variation of $Z$ at Addis-Ababa does not show any decrease corresponding to the decreases at Trivandrum.

In Fig. 15 are described the storm time variations of $H$ and $Z$ field at Indian stations during the storm beginning at 1015 hrs LT on 25 July 1981 and having the peak depression of $D_{st}$ index during the nighttime hours. The storm shows a two-step decrease of $D_{st}$ index at 1010 hrs LT and 1830 hrs LT. The $H$ field at any of the stations shows fluctuations synchronously with the fluctuation of $D_{st}$ index. The $Z$ field at the equatorial stations showed large decrease at times corresponding to large changes of $H$ field. The main decrease of $Z$ was at 1930 hrs LT on 25 July and not at the time of minimum of $D_{st}$ index.

In Fig. 16 are shown storm time variations of $H$ and $Z$ field at Indian stations on 30 Mar. 1990. The SSC was at 1220 hrs LT and the main phase started almost immediately afterwards and minimum $D_{st}$ index $= -170$ nT was observed at 1630 hrs LT in the afternoon. Storm time minimum $\Delta H$ at Trivandrum was $-250$ nT and at Alibag it was only $-180$ nT. This
is an example of the enhancement of storm effects in $H$ field during the daytime hours at an equatorial electrojet station. The $Z$ field at Trivandrum showed a drop of $-120$ nT at 1330 hrs LT. The magnitude of depression in $Z$ field at other stations decreased with increasing distance from the equator. Minor decreases in $Z$ were evident even at off-electrojet low latitude stations Hyderabad and Alibag. Thus, the very fast increase of equatorial ring current causes induction effects at larger extent of latitudes.

Figure 17 shows storm time variations in $H$ and $Z$ field at Indian stations due to storm on 19 Sep. 1989 with its peak intensity around midday hours. Comparing the parameters $\Delta H$ (TRD – ABG) it can be inferred that there was no counter electrojet either on 18 or 19 Sep. 1989. The weak normal electrojet at Trivandrum, in fact, counteracted on the storm time decrease of $Z$ field. The ionospheric current due to the normal electrojet produced positive change in $Z$ at all stations near the electrojet fringe stations. This positive $\Delta Z$ was opposed by the negative $\Delta Z$ due to the induced current with its source current at the ionospheric and magnetospheric regions. In this case, the minimum $D_{st}$ index was quite low, being $-270$ nT, but this decrease was spread over two hours. So the depression in $Z$ field at equatorial stations was comparatively weak.

In Fig. 18 are shown storm time variations of $H$ and $Z$ field at Indian stations following a SC at 0451 hrs LT (75 °E) on 28 Nov. 1959. The main phase onset was at 0830 hrs LT and the minimum $D_{st}$ was $-165$ nT at 11.30 hrs LT. The minimum $D_{st}$ index occurred exactly when a very strong noontime counter electrojet was observed at equatorial stations. The $H$ field at TRD had decreased by 230 nT at noon with respect to its midnight value, while corresponding decrease of $H$ at Alibag was only 130 nT. Thus, counter electrojet currents of 100 nT was flowing over Trivandrum at noon hours. The $D_{st}$ index showed a decrease of $165$ nT at 1130 hrs LT, when the storm time decrease of $H$ at noon was $-307$ nT at TRD, $-280$ nT at KOD, $-240$ nT at ANN and only $-139$ nT at ABG. The decrease of $Z$ field at TRD was 110 nT at 0930 hrs LT, but at other equatorial stations KOD and ANN, the $\Delta Z$ showed an increase of about 50 nT. It seems that the counter electrojet band current had over-compensated the effect of induced currents. It is interesting to find that even the low latitude station
ABG had observed an increase of $Z$. This presents an excellent example of midday enhancement of the magnetic storm over the magnetic equator.

In Fig. 19 are shown the storm time variations of $H$ and $Z$ field at Indian stations based on actual hourly mean data for the storm on 22-23 Nov. 1975, originally studied by Rajaram et al.\textsuperscript{40} on the basis of 13-h running mean data. It can be seen that $\Delta H$ (TRD–ABG) showed about 40 nT depressions around midday hours on both the days, indicating the existence of a counter electrojet current. The storm main phase onset on 22 November was after the

![Graph showing storm time variations of $H$ and $Z$ fields at Indian stations on 22 Nov. 1975](image1)

![Graph showing storm time variations of $H$ and $Z$ fields at Indian stations on 23 Nov. 1975](image2)

**Fig. 18** — Storm time variations of $H$ and $Z$ fields at Indian stations on 28 Nov. 1959 with a main phase minimum $D_s$ and the strong electrojet occurring at local noon hours

**Fig. 19** — Storm time variations of $H$ and $Z$ fields at Indian stations following a SC type of storm at 0400 hrs LT on 20 Nov. 1975 along with corresponding variations of $D_s$ index and of $\Delta H$ (TRD–ABG) [The storm time hourly deviations of $H$ and $Z$ fields at Trivandrum are also shown for comparison with storm time hourly means.]
counter electrojet event had ended, and the main phase end was at midnight of 22-23 November. Thus, the storm time variations were not affected by counter electrojet. There were large fluctuations of $H$ field at every station during the main phase of the storm. The $Z$ field at every equatorial station showed a decrease of about 50 nT at 1630 hrs LT. The 3-hourly running mean of the storm time variations of $H$ and $Z$ at Trivandrum shows a decrease of $H = -56$ nT at 2130 hrs LT and of $Z (= -30$ nT) at 1530 hrs LT when $\Delta H$ (TRD) was decreasing very fast. The comparatively small storm time variations detected by Rajaram et al. was due to the fact that they had used 13-h running mean data for their analysis. The midday counter electrojet on 23 Nov. 1975 occurred during the recovery phase of the storm. The concurrent decrease of $H$ field and increase of $Z$ field were due to the ionospheric counter electrojet current and not at all due to the magnetospheric ring current.

Thus, on individual storm events the changes in $H$ and $Z$ at equatorial electrojet stations are due to combined effects of magnetospheric as well as ionospheric currents and their induced currents.

The magnetic field variations observed on the surface of the earth comprises the primary fields generated by the external current in the ionosphere or the magnetosphere, plus secondary fields produced by the currents induced in the solid earth and oceans by the primary field variations. Chapman had addressed the problem of large scale and uniform global induction problem with the concept of image current. If the conductivity of the earth’s interior is assumed to be infinite at depth $d$ and lower, then the surface magnetic field effects can be calculated using Chapman’s electrojet Eqs (1) and (2) assuming the inducing current to be at a height of $h+2d$ in the direction reversed to the source current.

When the lateral changes in conductivity are of limited space, the process is called anomalous geomagnetic induction. The effective way of summarizing the main induction features can be better solved by the use of transfer functions. The vertical external field is, to a good approximation, cancelled by the internal uniform $Z$ field. The observed $Z$ variations are generated by local distortions of the internal current distributions. The anomalous part of the $H$ field is assumed to be small.

The network of magnetic stations in India is all north of the dip equator. The southernmost station Trivandrum had dip latitude = 0.3°S during 1958 and 0.3°N during 1994. Prof. Kitanura of the University of Kyushu, Japan had operated a set of digital fluxgate magnetometer at Peredinia (PRD), Sri Lanka (dip lat., 1.3°S) during 1993-1994. The hourly mean data of $H$, $D$ and $Z$ were provided to the present worker who made a detailed comparison of these data with those at Trivandrum. Ettayiapuram was conjugate to Peredinia (dip lat. = 1.3°S). In Fig. 20 are shown the mean daily variation of $H$, $D$ and $Z$ at PRD and TRD for the three different seasons of the year. It is seen that $S_\delta(H)$ at the two stations were almost of the same magnitude with a seasonal maximum during the equinoxes. The $S_\delta(Z)$ showed a large positive maximum and were shifted in time with respect to the same at TRD. The observed $\Delta Z$ at PRD was due to the combined positive effect of the ionospheric current as well as the due to the induced current. During the counter electrojet day, $\Delta Z$ at PRD was less positive than at ETT or KOD, because at PRD the ionospheric current effect was negative during the CEJ and the induced current was positive, while at ETT both the ionospheric and induced currents caused a positive change of $\Delta Z$ during the CEJ. The effects of SC and of the magnetic storm were very similar at PRD and TRD.

Arora proposed a conductor of half width of 30 km at a depth of 25 km in Palk Strait to explain the abnormal $S_\delta$ variations of the $Z$ field at Indian electrojet stations. He modelled the variations of $H$ and $Z$ 300 km north to 300 km south of the dip equator in Indian longitude taking into account the

![Fig. 20 — Quiet day solar daily variations of $H$ and $Z$ fields averaged for three seasons of the year 1993-94 at the equatorial electrojet stations Trivandrum (TRD) and Peredinia (PRD)](image-url)
effect of an electrojet current of 300 km semi-width at an altitude of 105 km and the conductivity channel of width 30 km at a depth of 25 km. Rastogi has discussed the results of his model in relation to the observations and these are briefly reproduced in Fig. 21. The result of the combined effect was a maximum of $\Delta Z (= 80 \text{ nT})$ at about 80 km south of the equator and a maximum of $\Delta H (= 120 \text{ nT})$ south of the equator. The daily range of $H$ at southern station PRD is found to be almost the same as that at TRD and $\Delta Z$ at southern stations is not as large as predicted by the model showing its inadequacy. It is suggested that anomalous conductive region of a much wider latitude extent has to be considered covering both southern India and Sri Lanka to explain the abnormal inductions in $Z$ field in Indian electrojet stations. The induction problems in the Indian equatorial electrojet are unique and the Chapman model of the elctrojet current cannot be utilised to delimitate the anomalous conduction layers. A better spatial distribution of observation points in Sri Lanka are very necessary to understand the phenomena.

5 Summary and conclusion

(i) The $S_q$ variation of the horizontal field $H$ at Indian electrojet stations fit fairly well the expectations from a Chapman’s ribbon type ionospheric current in the ionosphere.

(ii) The $S_q$ variations of the vertical field, $Z$, show abnormal positive peak noon and broad minimum in the afternoon at stations within 250 km from the magnetic equator.

(iii) There are systematic variations in the ratio of minimum $\Delta Z$ ($\Delta Z_{m}$) and the $\Delta H$ at the equator ($H_0$) with the time of the day, requiring a proper explanation.

(iv) The $S_q(Z)$ at Trivandrum and Ettayiapuram reflects the time derivative of $S_q (H)$ at these stations suggesting an induction effect due to current induced inside the solid earth.

(v) The counter electrojet events reflect the reversal of the daily variations of $H$ as well as $Z$ fields at any of the electrojet stations in India.

(vi) Nighttime bay events, show similar positive deviations of $H$ as well as $Z$ fields with large value of the ratio $\Delta Z/\Delta H$ at station closer to the equator, suggesting induction effect due to a uniform E-region ionospheric current.

(vii) During the International Geophysical Year, the magnetic storms showed decrease of $Z$– largest at Trivandrum, less at Koror and none at any other electrojet station. The decrease of $\Delta Z$ occurred few hours before the storm time minimum of $\Delta H$ when the $\Delta H$ was decreasing rapidly.

(viii) Along Indian longitudes, the largest storm time $\Delta Z$ occurs at Trivandrum and systematically decreasing magnitude of $\Delta Z$ is observed at stations further away from the equator.

(ix) The storm time decrease of $Z$ occurs both during the night as well as during the daytime. The observed daytime $\Delta Z$ is the combined effect due to eastward ionospheric and westward magnetospheric current.

(x) Storms with main phase during the midday hours show an abnormally large decrease of $\Delta H$ causing a counter electrojet.

(xi) Peredinia, a station in Sri Lanka about 1°S of the magnetic equator, showed the daily variation of $Z$ very similar to that observed at Trivandrum.
The idea of a small conductor in Palk Strait does not seem to explain the observed induction anomalies in the variations of $H$ and $Z$ low latitude stations in India and Sri Lanka.

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