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Transient Variation of the Electromagnetic Induction Due to Equatorial Electrojet

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Abstract: Electromagnetic inductive response of the electrically conducting Earth's interior to geomagnetic variations can be inferred from the magnetic Z-H or the magnetotelluric E-H relations. Using the magnetic Z-H relation of 5 stations across the Indian, African and American electrojet sectors, the transient variation of the electromagnetic inductive response of the subsurface lateral conductivity due to equatorial electrojet have been investigated during quiet conditions. The five selected equatorial electrojet stations are Trivandrum (TRD), Annamalainagar (ANN), Ettaiyapuram (ETT), Addis Ababa (AAE) and Huancayo (HUA). Hourly data of H and Z from the equatorial stations were analysed for regular solar quiet variation due to electrojet by taking the hourly departures from midnight values and effected correction due to non-cyclic variation. The ratios of regular variation in Z to that of H, $\Delta Z/\Delta H$, are taken and the first difference of its one-hourly values taken as an estimate of inductive response. Hourly profiles of the variations of ΔH, ΔZ and $\Delta Z/\Delta H$ of 60 magnetic quiet days were examined. Daytime source effect due to electrojet is noticed. The electromagnetic inductive response is negligible in daytime around local noon, when the electrojet source field has zonal symmetry, in all sectors. Strong inductive responses are obtained at the rising and decay periods of the electrojet. The observed inductive response is shown to be in agreement with the electromagnetic theory. The strong inductive responses observed at the rising and decay periods are shown, from existing numerical models and prior experimental observations, to be due to the return currents of equatorial electrojet. As expected and in consonant with the theory of electrojet dynamics, no nighttime induction effect was observed. The result represented the first observational evidence of the theoretical model of Ducruix and thus validated the controversial finding of Fambitakoye.

Key words: Equatorial electrojet, electromagnetic induction, geomagnetic variations, transient

INTRODUCTION

It is an established fact by now that the daytime dynamo E region of the ionosphere in the neighbourhood of magnetic dip equator consists of two layers of currents responsible for the quiet solar daily variations; one known as the worldwide Sq, flowing at an altitude of 118±7 km, the other one is the intense non-uniform east west current named as equatorial electrojet, EEJ, by Chapman (1951) which flows at a lower altitude of 106±2 km (Chapman, 1951; Richmond, 1973; Rastogi, 1975; Onwumechili, 1997). This intense eastwards current often changes direction on certain days, mostly at morning and evening periods and flows westwards. This westwards flowing electrojet was named 'counter electrojet' by Gouin (1962). The EEJ is responsible for the manifestation of an enhanced non-uniform H field with sharp spatial gradients resulting in large Z-variations in the region.

Magnetotellurics and geomagnetic depth sounding are the two established methods of estimating the induced response of a laterally inhomogeneous sub-surface. In the former, the Tikhonov-Cagniard impedance, expressing the relation between Electric (E) and magnetic (H) fields components, forms the fundamental EM response function. In the latter, the transfer functions relating the anomalous vertical field variations (Z) to the normal horizontal field component H are used to map the lateral conductivity (Schmucker, 1970). ΔZ, which represents the spatial gradient of the horizontal current intensity, shows greater response to induction than H (Price, 1967). Mayaud (1973) reported that the rate of induction due to electrojet can be estimated by using the ratio $\Delta Z/\Delta H$ and asserted that such ratios are highly sensitive to the importance of the induced fields since internal effects are subtracted from the external effects in Z while they are added in H.

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The ratios ΔZ/ΔH for short period magnetic variations have been employed to study several aspects of EM induction at equatorial region. The daytime to nighttime ratios of ΔZ and ΔH have been used to distinguish contributions to induction effects from primary ionospheric currents from those flowing in the magnetosphere at two electrojet stations: Trivandrum (TRD) and Annamalainagar (ANN) (Papamastrokis and Haerendel, 1983a). Chandrasekhar and Arora (1994) considered the daytime (0600-1800 h LT) and nighttime ratios (1801-0559 h LT) of ΔZ/ΔH for magnetic storms of January 28-29, 1980 and February 15-16, 1980 and suggested that the reduction in daytime ratios ΔZ/ΔH at stations close to the periphery of the electrojet is due to the mutual balance of external and internal parts in ΔZ while the reduction observed near the center of the electrojet axis was interpreted to indicate the weakening of the intensity of induced currents due to the presence of the induced currents due to the presence of the higher order spatial derivatives in the non-uniform source field.

The electromagnetic induction at equatorial region due to solar flares and other disturbances has been treated in the works of Rastogi (1999, 2001 and 2004). The EM induction response due to coastal effects has been studied at different locations/sectors: Indian sector (Nityananda *et al*., 1977; Rajaram, *et al*., 1979), American sector (e.g. Schmucker, 1963), Australia (e.g. Parkinson, 1963), USSR (e.g. Rokitjansky *et al*., 1963), Italy (Simeon and Sposito, 1963). The anomalies in EM inductive responses due to non-uniformities in lateral composition have been investigated by Whitham (1963), Schmucker (1963, 1970), Nityananda *et al.* (1977), Rajaram *et al.* (1979), Banks (1979), Papamastrokis and Haerendel (1983a, b), Singh and Agarwal (1983), Arora (2000) and Rastogi (2004). Schmucker (1970) observed that first indications for lateral non-uniformities come from the study of the diurnal geomagnetic Sq variations which have their main attenuation in mantle region.

It has been confirmed that induction sources during ionospheric distubances are quite different from those associated with regular electrojet variations (Fambitakoye and Mayaud, 1976; Ducruix *et al*., 1977; Vassal *et al*., 1998). Vassal *et al.* (1998) conducted a study of the variations of the Earth's electromagnetic field at West African EEJ zone during the IEEY, obtained some fascinating results and reiterated the necessity for further investigation of the transient variation of EM inductive response during quiet conditions at equatorial zone. Recently, Rastogi (2004) published a detailed review and interesting results on electromagnetic induction based on observation of fluctuation in Z and ratios ΔZ/ΔH due to equatorial electrojet mainly at disturbed conditions. The present study is aimed at investigating the transient variation of the EM inductive response due to regular daily variation in the equatorial electrojet during magnetic quiet condition with the objectives of understanding the variation pattern and the mechanisms responsible for the variation due to the localised phenomenon in the region.

Data analysis: Hourly profiles of Horizontal component (H) and vertical component (Z) of five EEJ stations Trivandrum TRD, Annamalainagar ANN, Ettaiyapuram ETT, Addis Ababa AAE and Huancayo HUA, whose coordinates are shown on Table 1, were analysed for regular solar daily variation for 60 quiet days of the solar minimum year 1986 (Sunspot number R = 13.4). The network of stations are selected to represent the Indian, American and African EEJ sectors. The distribution of Ap for the days considered are as follows:

Ap	2	3	4	5	6
Number of days	5	15	23	15	2

Data for TRD, ANN, HUA and AAE were obtained from the website of the World Data Centre-C2, Kyoto, while that of ETT was obtained courtesy of the National Geophysical Research Institute, Hyderabad, India. The concept of local time was considered. The variation in H (ΔH) and Z (ΔZ) were obtained by correcting the hourly departures, obtained from the difference between the hourly values and the midnight baseline values, for non-cyclic variation (Matsushita, 1967). Figure 1 illustrates the daytime variation of ΔH, ΔZ and ratios ΔZ/ ΔH on a typical day quiet day, 13th January 1986 (Ap = 4) while Fig. 2 shows the massplots of the diurnal variation of ΔH, ΔZ and ratios ΔZ/ ΔH over the entire period considered. The one hourly fluctuation of ΔZ/ΔH was obtained by subtracting the hourly ΔZ/ ΔH of the preceding hour from the succeeding hour values. The ratio of one-hourly difference, ΔZ/ΔH, is taken as the harmonic inductive response and reflected in Fig. 3.

Table 1: Geographic and geomagnetic parameters of the equatorial electrojet observatories

	Code	Geog.		
Station	Lat. N°	Long E°	Lat. (N°)	Geomagnetic
Trivandrum	TRD	8.29	76.57	-1.2
Addis-Ababa	AAE	9.0	38.8	5.3
Ettaiyapuram	ETT	9.1	78.0	-0.6
Huancayo	HUA	-12.0	284.7	-0.6
Annamalainagar	ANN	11.4	79.7	1.4

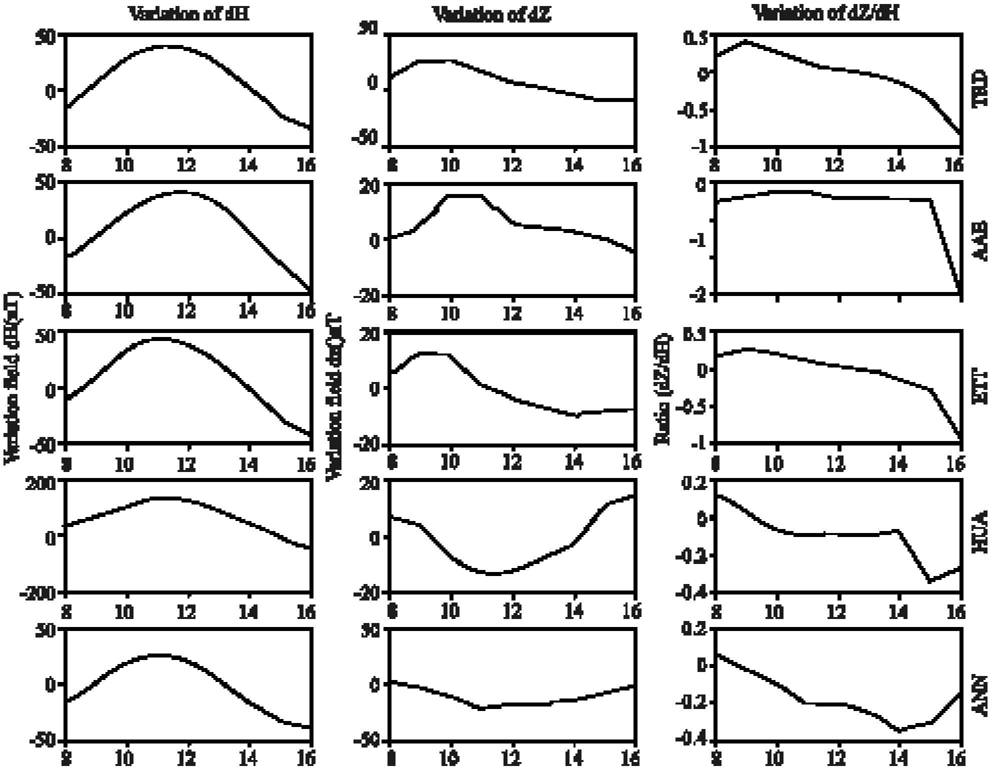


Fig. 1: Daytime variation of dH, dZ and dZ/dH on 13th Jan 1986

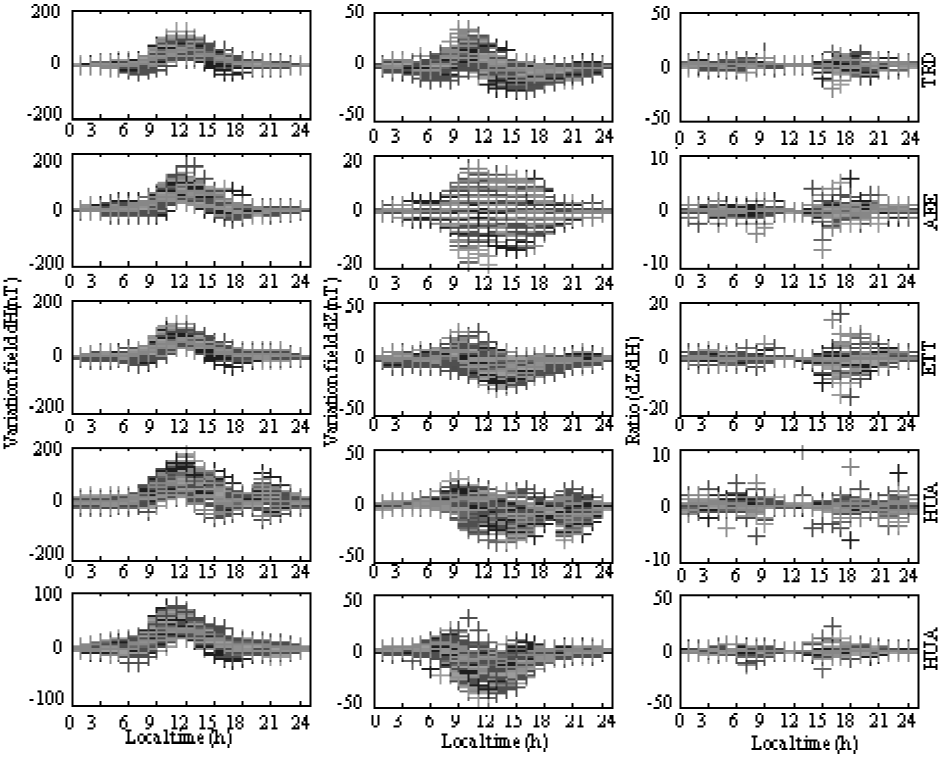
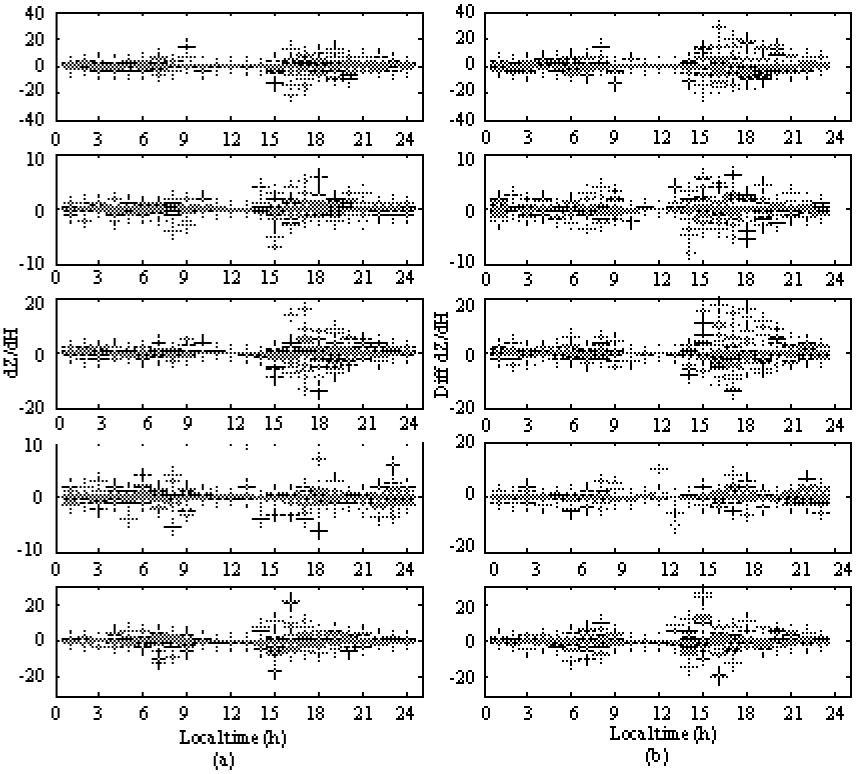


Fig. 2: Massplots of the hourly values of dH, dZ and dZ/dH



(a) (b)

Fig. 3: Massplots of the hourly values of (a) dZ/dH and (b) one houly harmonics

RESULTS

Figure 1 and 2 clearly indicate that the induction effects due to electrojet exhibits diurnal variation such that the nighttime variation is much greater than daytime. The nighttime induction events have been discussed by several authors and attributed to non-ionospheric sources (e.g. Papamastrokis and Haerendel, 1983a; Chandrasekhar and Arora, 1994). Figure 2 illustrates the daytime variation of ΔH, ΔZ and ratio ΔZ/ ΔH on a typical quiet day, 13th January, 1996 (Ap value 4) at all the stations considered. Figure 2 illustrates the diurnal variations of ΔH, ΔZ and ratios ΔZ/ ΔH for all the 60 days. It equally shows at a glance the variability of the quantities from one day to another at a fixed hour. Figure 3 illustrates the one-hourly rate of fluctuation of the induction effect. Considering the variability of the ratios ΔZ/ΔH in Fig. 2 and 3. It is obvious that the induction effects exist in daytime with negligible impact observed at the period of maximum of the jet, that is about local noon and noticeable effect at the period of rising and decay of the jet. We focus our discussion on the daytime observation of the variation of electromagnetic induction effect.

Among the stations, higher magnitudes of ΔZ/ ΔH were observed at TRD, as evident in the Fig. 4 where the scale of the TRD data had to be extended beyond universal limit. This obviously must be due to coastal effect, which amplifies the induced field at the station. These have been extensively discussed in the works of Nityananda *et al.* (1977) and Papamastrokis and Haerendel (1983a, b).

In a result that aroused controversy/crictisms, Fambitakoye (1973) analysed magnetic field variations associated with the EEJ along a north-south profile in central Africa and discovered a negligible internal part of the daily variation due to EEJ (designated as S_R^E) near local noon. Ducruix *et al.* (1977) later used mathematical model to show that the near local noon negligible nature of the electromagnetic inductive response due to EEJ is in consonance with the theory of electromagnetic induction.

The first report of negligible induced effects due to EEJ by Fambitakoye (1973) aroused an apparent conflict due to the misinterpretation of POGO satellite observational data, as evident in the works of Mayaud (1973). Fambitakoye and Mayaud (1973) took a second look at the results of Forbush and Casaverde (1961) and concluded that the ratios of ΔZ/ΔH over Peru indicated negligible induced effects at local noon.

As well observed by Ducruix *et al.* (1977), published data as at that period were often for local noon observations and so did not permit hourly profile observation of induced effects. Rather analyses were based on daily ranges which consider the local noon values and the nighttime baselines.

DISCUSSION

For proper understanding, we review the theoretical presentation of Ducruix *et al.* (1977) where the electrojet was modeled as a system of electric currents in the ionosphere. They considered both the disturbed and regular daily variations. This present study focuses only on regular variations and so we highlighted aspects that are relevant to this work. Let B_e be the magnetic induction related to the external currents that flow in the electrojet, B_i be the magnetic induction related to the induced currents that flow in the conducting solid earth and B be the total magnetic induction. Thus $B = B_e + B_I$. Ducruix and collaborators considered a horizontal path, C, drawn on a sphere of radius R inside the conducting earth, running for some length beneath the electrojet along the equator. In case of the regular Electrojet daily variation, such as we considered, the conducting earth moves with respect to the external currents with a velocity U; in the steady state the induction equation is:

$$\eta\nabla^2 B_I - U.\mathrm{grad}\,B_I = U.\,\mathrm{grad}\,B_e = (U/R)\,(\partial B_e/\partial \varnothing)$$

Where $\varnothing$ is the longitude and U is the linear speed of rotation of the earth at the equator. Moreover,

$$\eta = (\mu\sigma)^{-1};$$

μ being the magnetic permeability and σ the electrical conductivity of the earth.

The source term for induction is the field of spatial variations $U\,(\partial B_e/\partial\varnothing)$. The net circulation integral for the density of induced currents around C is

$$\int_C J_q.\,dl = -\,\sigma\Phi_q/T \quad (T = 24\text{ h})$$

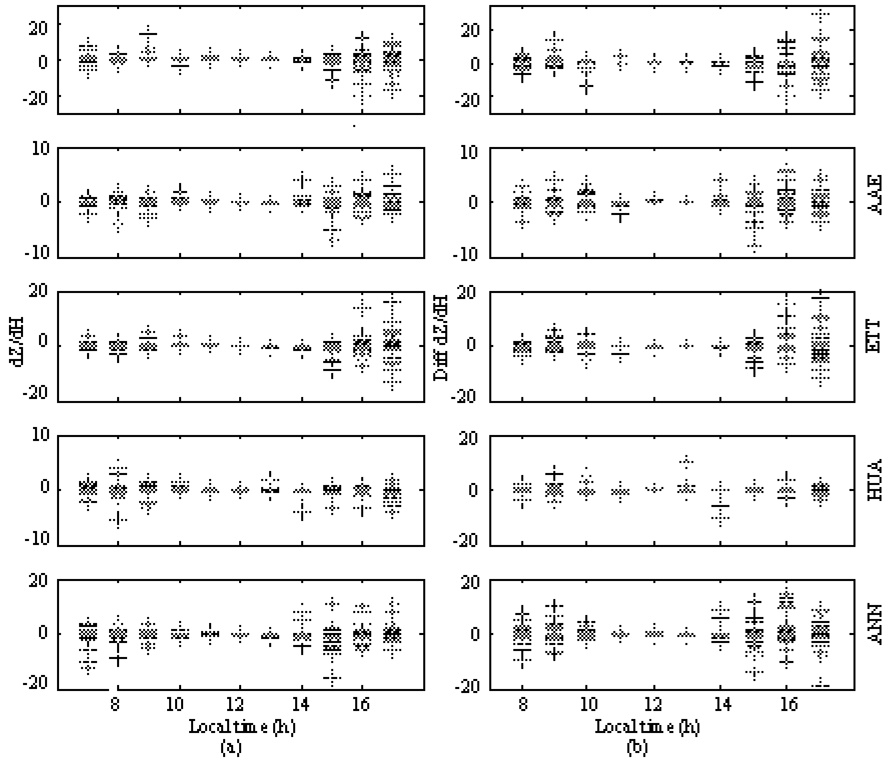
Where Φ_q is the net flow of $(\partial B_e/\partial\varnothing)$ across C. Thus J_q is proportional to $(1/T)(\partial B_e/\partial\varnothing)$. J_q is the density of internal induced currents. They asserted that in particular close to the Sun meridian (local noon) the electrojet has almost cylindrical (zonal) symmetry, $(\partial B_e/\partial\varnothing)$ is close to zero and the induced effects of the regular variation due to electrojet should be negligible. Their theoretical computation also yielded an expectation of "strong induced electrojet effects" at sunrise and sunset which according to them "would give us information about return currents at low latitudes."

Return current effects: Suzuki (1973) charted the flow of the return currents of the EEJ using the set of IGY observatory data of Matsushita and Maeda (1965) from where we identified the relevant results:

- The return current is more intense close to the magnetic dip equator.
- Nearly all the eastward current would have returned between the equator and Sq focus.
- The driving force of the return currents is the polarization field produced by the mechanism that the currents collected in the morning side of the equator because of high conductivity, cannot escape from there in the afternoon side against the lower conductivity outside the equator.
- The return currents begin to leave the equator gradually after the peak of the jet around 11 LT H.
- The outgoing currents are largest between 13 LT h and 14 LT h and the incoming ones are largest around 8 LT h.

Fambitakoye *et al.* (1976) showed that the magnetic variation signature at the equatorial region is a combination of the worldwide part of Sq (S_R^P), eastward part of the electrojet S_R^E and the westward part of the electrojet. Hesse (1982) noticed the "waviness" of the latitudinal profiles of hourly records of North Eastern Brazilian stations on quiet days during the rise and decay of electrojet. This "waviness" which disappeared during the period of maximum strength was attributed to the westward return currents. The westward part referred to by Fambitakoye *et al.* (1976) was qualified by Onwumechili (1992) as the return current responsible for electrojet depression often observed at periods 8-10:30 LT and 11:30-15:30LT. Obviously return currents exhibits significant influence in the ionospheric current systems during the rising and decay periods of EEJ. In other words, the return currents must be responsible for the electrojet induction activities during the pre-maximum era and post-maximum era as illustrated by Fig. 2-4.

Rastogi (2001) has reported that "the sfe (Z) at TRD is positive for all events during normal electrojet period and negative during counter electrojet period. The sign of ΔZ at Annamalainagar ANN is positive as well as negative and no reason for this differential effect is identified at present." Earlier Onwumechili (1992) observed that the return currents flow westwards when the electrojet is eastwards; and they flow eastwards when the electrojet reverses into CEJ and flow westwards. We



(a)

(b)

Fig. 4: Massplots of the daytime hourly values of (a) dZ/dH and (b) one houly harmonics

therefore suggest that the reversal of sign or direction of ΔZ observed by Rastogi (2001) is a reflection of the change in direction of the return currents, in response to reversal in the direction of the regular electrojet.

Onwumechili (1992) concluded that "the equatorial ionospheric current system is basically in two layers, it is suggested that the lower layer including the return currents around 5 degrees dip altitude, be associated with the equatorial electrojet; and that the weak upper layer that maintains more steady altitude extent everywhere be associated with the worldwide part of the Sq currents" (Onwumechili, 1997). Suzuki (1973) estimated the degree of the contribution of the return currents to the ground magnetic variations and found that they "are mostly less than ten and rarely twenty percent of those of the regular electrojet variation." Onwumechili (1992) concluded that the westward return currents are directly and permanently connected with the eastward EEJ. Vassal *et al.* (1998) recently argued a different source field, which is part of the regular EEJ, to be the source of induction field in the daytime equatorial zone. In their words "During quiet magnetic situations, our results demonstrated the existence of two different sources. One of these, the S_R^E source, was responsible for most of the magnetic diurnal variation and corresponded to the well-known magnetic signature of the equatorial electrojet. The other source (the $S_R'^E$ source) was responsible for most of the electric diurnal variation and was also likely to be an ionospheric source. Electric and magnetic diurnal variations are therefore related to different ionospheric sources...". From the above discussion it is obvious that three main currents are present in the daytime quiet dynamo ionosphere viz.; Worldwide Solar quiet daily variation Sq, equatorial electrojet and its return current. Suzuki (1973)'s claim that the return currents have negligible effects on the ground magnetic variation and our claim of its strong electromagnetic induction effects as expected by Ducruix *et al.* (1977) suggest that the '$S_R'^E$' source expected by Vassal *et al.* (1998) in the excerpt above must be the return currents of the electrojet, which satisfies all their expected attributes.

CONCLUSION

The present study has yielded some new observational results on the transient variation of electromagnetic induction due to regular equatorial electrojet. Data of hourly profiles of 60 quiet days from five stations (Trivandrum TRD, Annamalainagar ANN, Ettaiyapuram ETT, Addis Ababa AAE and Huancayo HUA) covering Indian, American and African equatorial electrojet sectors, were analysed for the inductive response and its one hourly harmonic. Daytime source effect due to electrojet is noticed. The daytime transient variation of inductive response is explained in terms of the normal electrojet and its return currents system. The electromagnetic inductive response is negligible around local noon, when the electrojet source field has zonal symmetry, in all sectors. In daytime, strong inductive responses are obtained at the rising and decay periods of the electrojet. The observed inductive response is shown to be in agreement with the electromagnetic theory. The strong inductive responses observed at the rising and decay periods are shown, from existing numerical models of Suzuki (1973) and Ducruix *et al.* (1977) as well as prior experimental observations of Fambitakoye (1973), Onwumechili (1992), Vassal *et al.* (1998) and Rastogi (2001), to be due to the return currents of equatorial electrojet. The nighttime inductive response is obviously due to magnetospheric sources. The result represented the first observational evidence of the theoretical model of Ducruix *et al.* (1977), thus validated the controversial finding of Fambitakoye (1973) and satisfied the expectation of Vassal *et al.* (1998).

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