Some Characteristics of the Equatorial Electrojet in Ethiopia (East Africa)

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Data from a very close network of ground magnetometers operated in Ethiopia (East Africa) within ± 5° of the dip equator during 1970-71 were used for studying the peculiarities of daily variation and storm effects. It was noticed that daily variation patterns near zero dip have enhanced magnitudes but do not bear a constant proportionality with patterns just outside the electrojet influence. The maxima and minima had different latitude dependences indicating possibly different causes. SSC magnitudes were enhanced near dip equator during daytime but the ratio of enhancement was not proportional to the electrojet strength. The analysis indicates a complex electrojet structure, probably a system of multiple current strips at different altitudes and having different latitude profiles not necessarily centered at the dip equator.

1. Introduction

The equatorial electrojet is a strong current in the ionospheric E region within a few degrees of the dip equator. Baker and Martyn explained it as an equatorial accentuation of the mid-latitude Sq system due to enhanced Cowling conductivity and predicted a half-width of about 3° in latitude and lead of one hour in the hour of maximum with respect to mid-latitude Sq. Using data from ground-based magnetometers several studies of electrojet region have been reported in the past. Thus, the electrojet is known to be strongest in the American longitudes and shows considerable day-to-day variability in strength as well as profiles. Of particular interest is the phenomenon of counter-electrojet, first pointed out by Gouin and Mayaud and studied extensively by several workers, wherein the electrojet seems to reverse its flow pattern during early morning and/or afternoon hours. All these studies were severely handicapped by the inadequate uniform coverage of the stations within the electrojet region. Attempts have been made recently to have a large network of closely spaced ground-based magnetometers in the equatorial region. Thus, Fambetakoye and Mayaud reported results from a network of 9 stations, 5 in the electrojet region (± 5° dip latitude) and 2 each in the vicinity to the North and South in Chad in the Central African Republic (long. 14°-19°E) during Nov. 1968-Mar. 1970. Separating the regular solar (Sq) variation into two components, viz. $S_{q}$ representing the effect due to mid-latitude "planetary" Sq current system and $S_{eq}$ representing the "supplementary" equatorial electrojet current confined to a narrow latitude band along the dip equator, they showed: (i) the permanence of counter-electrojet in the morning hours and frequent occurrence in the afternoon hours, (ii) frequent occurrence in the afternoon of a secondary reversed current ribbon, roughly twice as wide as the main ribbon, (iii) large variability in the ratio of $S_{q}$ to $S_{eq}$, (iv) significant north-south asymmetries in the total field and $S_{q}$, (v) shifting of the electrojet centre by about 40 km to the north during the counter-electrojets, and (vi) inhibition of the normal development of $S_{q}$ (reduction in the electrojet strength) when irregular short-term fluctuations occur on some days. Fambetakoye et al. have offered explanations for some of these in terms of possible ionospheric east-west winds at high altitudes (125-200 km) and plasma instabilities as envisaged in the physical model of the electrojet suggested earlier by Richmond.

A much more extensive network was operated in Ethiopia (long. 36°-44°E) from Dec. 1970 to May 1971 in a much restricted latitude range (± 5° dip lat.) but consisting of 38 stations. Preliminary results were presented by Porath et al. who showed that: (i) there was a north-south asymmetry in the daily range, the similar dip latitudes in the southern region showing larger ranges, (ii) the Z variation showed north-south asymmetries not only in amplitude and sign but in spectral composition also, the 24-hr, 8-hr and 6-hr components showing dissimilar behaviours, (iii) the planetary Sq and equatorial supplementary electrojet seem to be mostly unrelated, (iv) assuming the electrojet effect as equivalent to that due to three model line currents at dip latitudes 0°, ±1.5° and ±3°, it was observed that the inner line currents were stronger, indicating essentially a
centering on the dip equator, but during afternoon counter-electrojets, the current intensities seemed to decrease more gradually with distance (or latitude) than the normal electrojet currents did, indicating possibly different mechanisms and/or altitudes for the reverse current flows in the ionosphere. (v) On some days, the electrojet showed a depression near local noon and its magnitude decreased more gradually with latitude than the normal electrojet strength and the depression occurred slightly earlier farther away from the equator. (vi) Morning counter-electrojets, the current intensities seemed to decrease more gradually with distance (or latitude) than normal electrojet, (vii) though the magnitudes of electrojet, \( S_q \) and their ratios changed greatly from day to day (by a factor of 3) the ratios of the daily mean value as well as amplitudes of first and second harmonics were similar from day to day, indicating similar day-to-day waveform changes for electrojet and \( S_q \). (viii) The inner electrojet currents (nearer the dip equator) had a larger proportion of higher harmonics (4 and 5) indicating larger peakiness nearer equator, (ix) on storm day, the electrojet part could maintain its regular form of daily variation and could have counter-electrojets too, and (x) SSC had larger magnitudes nearer equator for some events.

In this paper, we have examined this Ethiopian data in greater detail and we present the results for a few quiet days and for some disturbance events.

2. Details of Stations and Presentation of Data

The array was initially formulated in order to study the electrical conductivity structure around the East African rift system. The deployment of stations is shown in Fig. 1 and details are given in Table 1.

2.1 Analysis for Quiet Days

The days 1 Dec. 1970 and 9, 16 Jan.; 28 Feb.-5 Mar. and 28 Mar. 1971 showed reasonably quiet day daily variation patterns. Fig. 2(a) shows the latitudinal variation of the daily range of \( H \) normalized to its maximum value near the equator. The station having maximum value is shown by a larger open circle. The range is defined as the maximum value of \( H \) during the day \( (H_{max}) \) minus the average \( H \) for 0000 to 0200 and 2200, 2400 hrs LT. The following may be noted:

(i) The maximum seems to occur not exactly at 0° dip but to its south. The average curve for all these days is shown at the top and bottom. The maximum seems to be between 0° and 0.5° South. For the Indian Zone, Sanker Narayan and Ramanujachary had also observed that the maximum range is not exactly at 0° dip but about 0.5°N.

(ii) After a sharp fall on either side of the 0° dip, the \( S_q \) ranges flatten out for latitudes exceeding 4°. Thus, station 1 MAK (+ 4° dip) may be considered as almost at the northern edge of the electrojet effect and station 6 ADI (+ 4.87 dip) just outside the electrojet effect. Considering the fact that these are ground observations, the actual electrojet region in the ionosphere will be confined to less than + 4.87 dip or even + 4.10 dip. On the southern side, data for 5 YAV (− 4.50 dip) are meagre but the ranges are larger than ranges for similar northern dip latitudes. Thus, a substantial north-south asymmetry with south showing larger amplitudes is seen in agreement with Porath et al. This could have brought an apparent southward shift in the electrojet centre. Or alternatively, the southward shift may be a primary feature so that similar southern latitudes would show larger amplitudes.

(iii) The shapes on all days are not alike. The days are arranged in such a way that the percentage range value of station 1 MAK (+ 4° dip) is in ascending order from bottom to top. Thus, \( S_q \) ranges at + 4° dip latitude can be as low as 30% and as high as 70% of the maximum ranges at about zero dip and the actual magnitudes are from 25 to 89 gamma but not in the same ascending or descending order. Thus, the \( S_q \) range at 1 MAK bears no relation with the total current strength at equator.

It needs to be checked whether, after removing the \( S_q \), the residual supplementary electrojet shows similar latitude dependences from day to day. The
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Fig. 2(a)—Plots of $H$ range versus dip latitude for 11 quiet days (dates indicated) with the maximum value (near equator) set at 100%. [The top and bottom dashed curves are averages for all these days. Actual $H$ ranges as well as percentages for a particular station (1 MAK, +4°10 dip) are indicated.]

Fig. 2(b)—Plots of excess $H$ range (over the $H$ range at reference station 6 ADI at +4°87 dip or in its absence, 1 MAK at +4°10 dip) versus dip latitude with maximum values (near equator) set at 100%. [Percentages for two selected dip latitudes (+3°22° and −2°83°) are indicated. The average of all these plots is indicated at the bottom (dashed curve).]

Fig. 2(c)—Plots of $H$ ranges of the supplementary electrojet obtained by subtracting the daily variation profile (3 min values) of the reference station 6 ADI (or 1 MAK) from the profile of every station, versus dip latitude. (Numbers represent percentages at two selected dip latitudes +3°22° and −2°83°. The top and bottom dashed curves are averages for all these days.)
$\text{Sq}$ could be removed scalarly by subtracting the range at 6 ADI (or in its absence, 1 MAK) from the range of all other stations and expressing the residues as percentages of the largest residue. Fig. 2(b) shows the latitude dependence of the residual ranges using 6 ADI or in its absence, 1 MAK as reference. All the plots have a general inverted cap shape but the electrojet centre still seems to be southward of 0° dip on some days. The percentage ranges at two fixed dip latitudes +3°22 and -2°83 are marked in Fig. 2(b). The values change in a wide range even for days having the same electrojet centre position. It seems, therefore, that the electrojet not only changes its centre by about ±0°5 from day to day but also its latitudinal profile, with profiles on the northern and southern sides not tallying most of the time. We have assumed here that the $\text{Sq}$ and supplementary electrojet have the same phase, i.e. the maxima occur at the same time. It is conceivable that even the profiles of the two may not be identical. Hence, the actual $H$ values (every 3 min) of 6 ADI or in its absence, 1 MAK were subtracted from the actual values of every other station and the daily ranges calculated from the residual daily variation curves so obtained. Fig. 2(c) shows the latitude dependence of the $H$ ranges so obtained. The day-to-day variability is still there though considerably less than that in Fig. 2(b). [Ranges at -2°83 dip are between 6 and 59% in Fig. 2(b) and only 32 and 60% in Fig. 2(c)]. Thus, some day-to-day changes in the position of the centre of electrojet and its northern and southern latitudinal profiles seem to be genuine.

We now proceed to examine detailed features on individual days:

1 Dec. 1970—Fig. 3 shows the daily variation pattern for 1 Dec. 1970 where the $H$ value of the reference station 6 ADI (+4°87 dip, actual values shown at the bottom) are subtracted from the $H$ values of every station, starting with stations nearer to equator plotted at the top. The day seems to be characterized by a broad peaked $\text{Sq}$ with a maximum at about 1230 hrs LT (magnitude 43 gamma) and a superposed supplementary electrojet with a roughly similar noon time pattern (maximum magnitude extra 54 gamma) but a conspicuous counter-electrojet in the morning hours (magnitude maximum 20 gamma at equator). A lack of any indication of a counter electrojet in the actual $H$ values of 6 ADI makes us believe that 6 ADI is adequate as a reference station outside the electrojet influence. The latitudinal distribution of the noon maximum value

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**Fig. 3**—Daily variation of $\text{Sq}(H)$ at the reference station 6 ADI (+4°87 dip, bottom curve) and the supplementary electrojet (station minus 6 ADI) at various locations starting near equator at the top, for 1 Dec. 1970 (Black patches indicate counter-electrojets)
is shown in Fig. 2(c) and shows the electrojet centre at about $-0.5^\circ$ dip. The latitude dependence of the counter-electrojet magnitude is shown in Fig. 4 (top curve). It seems that the counter-electrojet has its centre at $0^\circ$ dip and the magnitude decreases on either side much faster than the noon-time intensity decrease shown in Fig. 2(c). Thus, at least in this case, the counter-electrojet decreased more rapidly with latitude as compared to the normal electrojet, in agreement with the finding of Porath et al.22

9 Jan. 1971—Fig. 5 shows a detailed plot for 9 Jan. 1971. The $Sq$ at the reference station 6 ADI ($+4.87^\circ$ dip) has a maximum around 11-12 hrs LT, (25 gamma) and a significant second maximum (16 gamma) around 17-18 hrs LT, at hours when normal $Sq$ is expected to disappear. This feature should be a magnetospheric effect. However, in the difference curves, the supplementary electrojet shows firstly a morning counter-electrojet of about 8 gamma and a sharper and earlier maximum (60 gamma at 1030 hrs LT). This is followed by a plateau type structure near 1300 hrs LT (the $Sq$ at 6 ADI has also a similar tendency); but at about 1430 hrs LT, an interesting feature is seen. At equator, there is a conspicuous trough here but the values are still above the zero level. However, at higher dip latitude an afternoon counter-electrojet develops in the northern latitudes but not in the southern latitudes where only a trough is seen with $H$ values still positive. It would thus seem that this counter-electrojet system is centered not at $0^\circ$ dip but much farther north (about $+2.4^\circ$ dip) (latitude dependence is shown in Fig. 6). An examination of the plots of $Z$ component also indicated a similar possibility. Whether normal and counter-electrojets are similar is presently a matter of controversy. This example would indicate radically different characteristics for the two. After the counter-electrojet, the $H$ values on 9 Jan. 1971 rise again significantly above the zero level at almost all locations at about 1600 hrs LT. The latitude dependence of this second maximum is shown in Fig. 7 and differs from the latitude dependence of the main peak at 1000 hrs LT [shown in Fig. 2(c)] in that the maximum magnitude occurs at $0^\circ$ dip for the 1600 hrs LT peak and $-0.5^\circ$ dip for the 1000 hrs LT peak in spite of the north-south asymmetry common to both.

16 Jan. 1971—Fig. 8 shows the daily variation patterns for 16 Jan. 1971. The $Sq$ at the reference station 6 ADI ($+4.87^\circ$ dip) has a very large daily $H$ range of about 80 gamma, but the superposed supplementary electrojet has a still larger range of about 120 gamma (total 200 gamma) at equator. Thus, this was a day of abnormally large $Sq$ and electrojet currents. A morning counter-electrojet had a maximum magnitude of about 9 gamma at $0^\circ$ dip. The latitude dependence is shown in Fig. 4 and shows a very high degree of north-south asymmetry. The $Sq$ has two peaks at about 1000 and 1130 hrs LT with a slight trough in between. However, the supplementary electrojet shows a small peak at 1000 hrs LT and the main maximum is at about 1130 hrs LT and has a latitude dependence as shown in Fig. 2(c). On the northern side, it compares with that for 9 Jan., but on the southern side, 16 Jan. shows a much steeper decrease with latitude and...
hence a lesser north-south asymmetry. The $S_q$ curve shows very low $H$ values at 1500 hrs LT but these are still positive. However, nearer equator an enormous counter-electrojet develops in the afternoon with a maximum magnitude of about 45 gamma below night level. Its latitude dependence plotted in Fig. 6 shows a broad maximum near 0° dip but significant north-south asymmetry. The recovery from the counter-electrojet seems to push $H$ values above the succeeding night level by almost 15 gamma at equator even at about 1800 hrs LT when $S_q$ has disappeared.

Fig. 8—Daily variation of $S_q(H)$ at the reference station 6 ADI (+4.87° dip; bottom curve) and the supplementary electrojet (station minus 6 ADI) at various locations for 16 Jan. 1971 (Black patches show counter-electrojet)

27 Feb.–5 Mar. 1971—Continuous data were available for this 7-day interval. Fig. 9 shows the continuous plot of hourly values for these seven days for $S_q$ at the reference station 1 MAK (+4.10° dip) at the bottom and supplementary electrojet at other stations. Data for 6 ADI (+4.87° dip) were not available for this interval. Instead, data for 6 YAV (−4.50° dip) were available; but as can be seen from the dashed curve superposed on the full curve for $S_q$ at 1 MAK, amplitudes at YAV are equal to or larger than those at 1 MAK. Thus, in spite of its higher dip latitude, 5 YAV seems to have more electrojet influence than 1 MAK. Hence, 1 MAK was chosen as a reference rather than 5 YAV. This 7-day interval is not quiet. The geomagnetic $D_{st}^{24}$ is between 0 and −40 gamma with several ups and downs throughout this interval (lowermost curve in Fig. 9). Unfortunately, interplanetary magnetic field data were not available. During the 5 days, some features (e.g. the spike at 1900 hrs LT on 27 Feb. have the same magnitude at all latitudes and hence must be of magnetospheric origin. 4 Mar. was definitely a disturbed day. The supplementary electrojet shows normal one hump pattern on 28 Feb. and to some extent on 1 Mar.; but on all other days, there is a marked two hump structure, the first roughly at 1000 hrs LT and the second at about 1500 hrs LT with a conspicuous minimum at about noon. This feature has been noted

Fig. 7—Latitude dependence of successive maxima and minima on different dates and LT as indicated, expressed as percentages of the maximum value (near equator) (Shaded portions indicate values dropping below daytime zero level)
who mention that the depression has a more gradual latitude dependence than the daily range. The whole period is also characterized by conspicuous counter-electrojets in the morning hours on all days. While on 4 Mar., evening depressions appear in the northern region only at dip latitudes exceeding $+2.0^\circ$ only. Some of these are near 1500-1600 hrs LT and would be counter-electrojets. However, others are mostly at 1700-1800 hrs LT or later and are thus in the nighttime and would imply enhanced Dst though it is not clear how Dst could be more at $+3^\circ$ dip as compared to $0^\circ$ or $+5^\circ$ dip. To study the longitudinal evolution of these patterns, data for electrojet from pairs of equatorial and non-equatorial stations at different longitudes would be useful. Fig. 10 shows the plot for the differences of $H$ values for the pair Kodaikanal and Hyderabad (75°E), 25 WON and 1 MAK (45°E) and Huancayo and Fuquene (75°W) at the same UT. The daily variation patterns are mainly single-humped at Kodaikanal on all days while the Ethiopian region shows clear two-humped structures. Huancayo shows fluctuations near noon but no two clear humps. Thus, peculiar daily variation patterns are restricted to very narrow longitudinal bands, in agreement with a similar earlier finding.9

Fig. 9—Daily variation of $Sq$ ($H$) at the reference station 1 MAK ($+4.10^\circ$ dip, bottom full lines) and 5 YAV ($-4.20^\circ$ dip, bottom dashed lines) and the supplementary electrojet (station minus 1 MAK) at various locations for the 7-day interval 27 Feb.-5 Mar. 1971 [Black patches show counter-electrojets. The bottom-most curve shows the variation of equatorial Dst ($H$) value]

Fig. 10—Daily variation of electrojet strength ($H_{equator}$ minus $H_{non-equator}$) for 27 Feb.-5 Mar. 1971 at different longitudes (Kodaikanal, 75°E; 27 DBZ 45°E; Huancayo, 75°W) (Full dots indicate local noons and open circles indicate local midnights)
The electrojet has a small morning counter-electrojet (about 10 gamma at equator) with a latitude dependence as shown in Fig. 4. The behaviour is somewhat erratic, probably because of smaller magnitudes. The pattern of the noon electrojet is quite different from that for the previous day. Thus, a smaller peak occurs at about 1130 hrs LT followed by a plateau and a larger peak at about 1500 hrs LT. The latitude dependence for the 1500 hrs LT peak is shown in Fig. 4 and for both peaks (1100 and 1500 hrs LT) in Fig. 7, showing the remarkable similarity. Thus, this whole pattern has evolved during the day without change in the centering or the latitude profiles of the electrojet.

3 Mar. 1971—Reference station 1 MAK shows an unusually broad peak between 1100 and 1600 hrs LT. The electrojet part is characterized by a morning counter-electrojet (about 10 gamma at equator) centred at 0° dip but decreases much more gradually in the south than in the north (Fig. 4). The noon pattern shows a first maximum at about 1100 hrs LT, followed by a very conspicuous trough at 1330 hrs LT, followed by a second maximum at about 1530 hrs LT. The latitude dependence for all the three is shown in Fig. 7. Whereas the two maxima show similar latitude dependences, the in-between minimum shows a significantly different pattern with values dropping below the zero level at some larger dips. Thus, the minimum seems to be caused by an altogether different reverse current system much broader in latitude than the normal electrojet. This is in agreement with Porath et al., who report that the depression magnitude decreases with latitude more gradually than the normal electrojet. However, our detailed plots show that the depression minimum occurs at about 1330 hrs LT at all latitudes and not earlier at higher latitudes as reported by them.

4 Mar. 1971—This day is the most disturbed in this sequence and theSq at 1 MAK shows a large depression from 1600 hrs LT onwards which is obviously a magnetospheric storm effect. Otherwise, the noon pattern is normal with a maximum near 12 noon. The electrojet pattern is very odd indeed. There is a morning counter-electrojet of about 10 gamma at equator centred at 0° dip but having a severe north-south asymmetry (Fig. 4), south showing much larger magnitudes. The noon pattern looks like a normal electrojet evolution up to about 1000 hrs LT followed by severe inhibitions resulting in large fluctuations. Fig. 11 shows a detailed plot. At its bottom the extreme south station 5 YAV (dashed
lines) shows a smaller $Sq$ magnitude in the morning hours as compared to 1 MAK (full lines) but larger magnitudes in the afternoon as if the evolution of $Sq$ has been delayed in the south. The storm effects at 1900 hrs LT are equal and synchronous at both the locations. The latitude dependence of the morning counter-electrojet is shown in Fig. 4 and though centred at 0° dip, shows a very large north-south asymmetry, south showing much larger magnitudes. For the noon fluctuations, the latitude dependences of the maximum at about 1000 hrs LT, minimum at about 1030 hrs LT, maximum at about 1130 hrs LT, minimum at about 1200 hrs LT, maximum at about 1215 hrs LT, minimum at about 1230 hrs LT and the final largest maximum at about 1500 hrs LT are shown in Fig. 7. Whereas the maxima show a similar latitude dependence, the minima have a much sharper latitude dependence, values going even below the zero level, thus indicating different sources for the maxima and minima.

MINOR STORM OF MARCH 4, 1971

Fig. 11—Daily variation of $Sq (H)$ at the reference station 1 MAK (+ 4·10° dip, bottom full lines) and 5 YAV (− 4·50° dip, bottom dashed lines) and the supplementary electrojet (station minus 1 MAK) at various locations for 4 Mar. 1971, a moderately disturbed day (Black patches show counter-electrojets)
For the hours near 1900 hrs LT where the storm $D_{st}$ is high, some stations show extra negative effects (painted black). The reason for this is not quite clear. At these LT, the ionospheric electron densities are negligible and hence E-region electrojet currents could not be playing any role. On the other hand, it is difficult to conceive a magnetospheric effect which gets accentuated at $\pm 3^\circ$ dip as compared to $0^\circ$ or $\pm 4^\circ 5^\circ$ dip. Whether ionospheric F-region is contributing to the ground $H$ vagaries due to peculiar neutral winds is a mute question.

5 Mar. 1971—This day was characterized by a very broad $Sq$ peak, from 1100 to 1700 hrs LT at the reference station 1 MAK. The supplementary electrojet showed a morning counter-electrojet with latitude dependence (as shown in Fig. 4) showing a centre probably at $0^\circ$ dip and a large north-south asymmetry, south exceeding north. The electrojet reaches a maximum at about 1130 hrs LT not smoothly but in an oscillatory fashion ($\pm 10$ gamma) with successive peaks and troughs at 1000, 1015, 1045, 1115, 1130, 1145 and 1215 hrs LT the highest being the 1130 hrs LT peak. These were seen in the $Sq$ at 1 MAK also, though with much smaller magnitudes and should, therefore, be considered as just equatorial enhancements of $Sq$. After 1215 hrs LT there was a drop of about 10 gamma and then a plateau (small peak at 1500 hrs LT) up to about 1600 hrs LT similar to the $Sq$ pattern. Fig. 7 shows the latitude dependences of these peaks and troughs. All maxima show similar patterns but all minima show sharper drops with latitude, thus indicating possibly different sources for the main electrojet peaks and the superposed troughs.

28 Mar. 1971—This day was characterized by a very smooth $Sq$ peaking at about 1130 hrs LT at 6 ADI ($+4^\circ 87^\circ$ dip) with a very large amplitude (about 85 gamma). The superposed supplementary electrojet was also large (about 60 gamma, total equatorial range about 150 gamma). The $Sq$ and electrojet patterns were very similar. There was a morning counter-electrojet of magnitude about 13 gamma at equator. The latitude dependence is shown in Fig. 4 showing normal behaviour. In the afternoon, there was a large counter-electrojet (magnitude 23 gamma at equator). Its latitude dependence is shown in Fig. 6. The centre seems to be around $+0^\circ 5^\circ$ dip and there is a very high north-south asymmetry with south showing higher magnitudes.

In all these studies, the group of stations 17 DEG ($+1^\circ 72^\circ$), 18 BAT ($+1^\circ 80^\circ$), 8 BOM ($+1^\circ 82^\circ$), 15 ELO ($+1^\circ 86^\circ$) are very near each other and yet do not always show similar magnitudes possibly due to anomalies in subsurface structure in this region.
Fig. 14—Latitude dependence of the magnitudes of SI (sudden impulses) of 11 and 12 Dec. 1970

almost double that of the 20 gamma observed at the non-equatorial location.

12 Dec. 1970—Fig. 13 shows a detailed plot of another SI event (1200-1230 hrs LT). The reference station 6 ADI (+ 4°87' dip) shows a rise of about 10 gamma in 2 min from 1203 to 1205 hrs LT and then a slow recovery to original level in the next 13 min (by 1218 hrs LT). The supplementary electrojet shows an extra rise of about 32 gamma in 2 min. Thus, the equatorial magnitude (32 + 10 = 42 gamma) is about 4 times the non-equatorial magnitude of 10 gamma.

These two SI events (11 and 12 Dec. 1970) occurred at 1328 hrs LT and 1203 hrs LT, respectively, and thus the latter event occurred earlier when the electrojet is expected to be stronger. Actual H plots at Addis Ababa showed that the H range for the latter event was only about 15% larger. This hardly seems to justify the 1 : 4 enhancement for the latter event as compared to 1 : 2 enhancement for the first event. Fig. 14 shows the latitude dependence for these events. There is a broad pattern near zero dip but the maximum is shifted south to about -1° dip. SI is caused by magnetospheric compression due to interplanetary discontinuities. As such it is a magnetospheric phenomenon. Its enhancement in the electrojet has region been reported long ago and a possible explanation is given in terms of hydromagnetic waves propagating downwards into the ionosphere and creating a polarization electric field as the wave-front hits the dynamo layer. This process needs detailed quantitative investigation.

The above events show that SI enhancements are not directly proportional to the electrojet strengths.

27 Jan. 1971—Fig. 15 shows the storm of 27 Jan. 1971. An SSC occurred at 0430 hrs UT and the top curves show H plots for the reference station 6 ADI (+ 4°87' dip, full lines) and the equatorial station 7 AWS (- 0°47' dip, dashed lines). Both show the SSC at 0430 hrs UT (0730 hrs LT) as expected followed by a rise up to about 0700 hrs UT (1000 hrs LT), a drop to initial level by 0900 hrs UT (1200 hrs LT) and then the main phase. Similar curves for pairs of stations at two other longitudes, Kodaikanal-Hyderabad at 75°E and Huancayo-Fuquene at 75°W are also shown for comparison. Next are shown the difference curves (H_equator minus H_non-equator) which
Fig. 15—The storm of 27 Jan. 1971 (SSC at 0430 hrs UT) (Upper portion shows actual $H$ values and lower portion the differences between equatorial and non-equatorial locations in different longitudes)

represent the supplementary electrojet. For the American longitudes, the storm occurred at 2350 hrs LT, i.e. at about midnight. The difference Huancayo minus Fuquene shows no significant fluctuations, thus indicating that the storm effects were roughly similar at equatorial and non-equatorial stations. At noon-time when the main storm was in full swing, the electrojet at Huancayo shows normal evolution from 0730 to 0900 hrs LT and then violent fluctuations and later a counter-electrojet at 1230 hrs LT. For the Ethiopian region, the storm started in the morning at 0730 hrs LT and $H$ values increased normally up to 0900 hrs LT and then showed violent fluctuations and a counter-electrojet from 1200 to 1500 hrs LT. For Indian longitudes, the storm started at 0930 hrs LT. By that time, the electrojet had already evolved normally and considerably but soon showed erratic fluctuations ending finally in a counter-electrojet between 1230 and 1600 hrs LT. Thus, stations wide apart in longitudes showed more or less similar LT patterns though the magnitudes for the morning fluctuations were smallest at Kodaikanal and largest at Huancayo, which is the usual characteristic of the normal electrojet also at these locations. The morning fluctuations in actual $H$ values could be characterized by successive maxima I, II, III,...IX as marked for the Ethiopian stations in Fig. 15 top and the latitude dependence of the magnitudes of these maxima and the in-between minima (reckoned from 0600 hrs LT as base) is shown in Fig. 16. The first maximum (Max I, top curve) was almost latitude independent implying that all latitudes showed the same magnitude and thus there was no significant equatorial enhancement for this feature which occurred at 0733 hrs LT. However, the succeeding minimum (Min I) at 0735 hrs LT and the succeeding second maximum (Max II) at 0800 hrs LT showed a considerable latitude dependence. The minimum at 0810 hrs LT (Min II) showed an odd behaviour, viz. a latitude dependence reverse to that of the earlier maximum. This implies that the second maximum (Max II) and the succeeding minimum are not just fluctuations of the same electrojet current but have two independent causes.
The next maximum at 0855 hrs LT (Max III) had the same latitude dependence as Max I but the succeeding minimum (Min III) at 0945 hrs LT had a latitude dependence different from that of Max II but similar to that of Min II. Thus, from 0730 hrs LT when the event started at about 0945 hrs LT, the maxima showed one type of latitude dependence and the minima showed a different type. It could be that the maxima were manifestations of evolution of normal electrojet on which reverse currents of different characteristics were superposed giving the various minima.

At 0955 hrs LT, a major maximum (Max IV) occurred, followed by many other maxima and minima and their latitude dependences are surprisingly similar (Fig. 16) probably indicating simple modulation of a single electrojet current. Soon after 12 noon, the initial phase of the storm was over and the $H$ values dipped below the zero level heralding start of the main phase of the storm. Max VIII at 1245 hrs LT was at this stage and its latitude dependence is quite different from that of the earlier fluctuation indicating a different source, which in this case is obviously the magnetospheric Dst. Even then, the succeeding Min VIII at 1310 hrs LT, Max IX at 1335 hrs LT and Min IX at 1415 hrs LT show latitude dependences similar to the earlier fluctuations.

Since the $H$ values are affected by ionospheric as well as magnetospheric changes, the pure electrojet effects would be seen only in the difference curves of $H$ values at equatorial and non-equatorial stations as shown in the lower half of Fig. 15. For the Ethiopian network, Fig. 17 shows the supplementary electrojet patterns for 22 stations. The SSC at 0729 hrs LT is not very conspicuous and up to 0855 hrs LT (Max III) the electrojet evolution may be considered normal. However, later maxima and minima (III, IV, V, VI, VII) are quite large and their latitude dependences are shown in Fig. 18 and are surprisingly similar except for Min VI, which shows an odd behaviour.
in the northern latitudes in that for these locations values at 1140 hrs LT touch the zero level and occasionally drop below zero. Thus, all these are modulations of a single current system. Between 1200 and 1600 hrs LT, there was a significant afternoon counter-electrojet (CEJ) and the latitude dependence of its magnitude is shown at the bottom of Fig. 18. It is somewhat different from the earlier plots and could imply a current system different from the normal electrojet current system.

9 Apr. 1971—Fig. 19 shows the storm of 9 Apr. 1971 which started with a SSC at 0430 hrs UT, the same as that of the earlier storm of 27 Jan. 1971. However, whereas the electrojets had very different evolution patterns at different longitudes [Kodai kanal (India) and Ethiopia], the electrojet showed similar UT patterns (maximum at 0630 hrs UT, minimum at 0800 hrs UT) rather than similar LT patterns which is rather surprising. The main phase started at about 0800 hrs UT and at about 1000 and 1200 hrs UT, the equatorial stations show much larger negative $H$ than the non-equatorial stations. If this is an ionospheric effect, as it seems to be so prominent in the difference curves (Fig. 19 bottom) only during daylit hours, these must be unusually strong counter electrojets (shaded black). At Huancayo, there is a very strong counter-electrojet at 0700-0800 hrs LT and then violent fluctuations in the electrojet strength. Thus, the electrojet evolution pattern at Huancayo was radically different from those at Kodai kanal or Ethiopian region.

3. Summary and Conclusion
The main features of this study for the Ethiopian region are as follows:
(i) Even on comparatively quiet days, the daily $Sq$ range of $H$ can vary in very wide limits (25 to 90 gamma) from day to day. The superposed supplementary electrojet is centred between 0° and 0.5° south dip latitude and can have an extra magnitude (total $H$ range at equator minus range at the reference station at the edge of the electrojet) of 40 to 80 gamma from day to day. But the $Sq$ and electrojet ranges seem to bear no relation to each other. Kane made a comparison between the $H$ ranges of the equatorial station Trivandrum and the
non-equatorial station Alibag in the Indian longitudes and the low correlation between these was shown to improve if the movements of the mid-latitude \( Sq \) focus were also taken into consideration. In the present case, this factor is likely to be of little consequence as ranges at nearby stations (0° versus 5° dip latitude) are compared. Thus, something very serious and drastic must be happening in the narrow electrojet strip ± 5° dip latitude over and above the equatorial enhancement near zero dip envisaged in the Baker and Martyn mechanism.¹

(ii) Even the profiles of the \( Sq \) and electrojet are not always similar. The \( Sq \) usually has a Gaussian appearance with maximum occurring anywhere between 1000 and 1500 hrs LT but usually near local noon; also the half-width varies considerably from day to day, the 50% reduction from the peak value occurring on some days within ± 2 hr while on some other days a broad peak occurs for several hours. The supplementary electrojet is sometimes almost parallel to the \( Sq \) pattern but on some days it may show considerably different patterns with narrow or broad maxima not necessarily one hour earlier than \( Sq \) as envisaged in the Baker and Martyn mechanism. Thus, the electric fields causing \( Sq \) and electrojet may not be completely identical.

(iii) The latitude dependence of the electrojet magnitude shows changes in the centre as well as in the shape from day to day with very large north-south asymmetries on some days but not on all days.

(iv) The electrojet profile has one or more of the following features: (a) a morning counter-electrojet, (b) a rise up to about noon, either smooth or having an undulatory structure, and (c) a subsequent fall to zero level by dusk which can be as (i) a broad plateau followed by a sharp drop, or (ii) a sharp fall to the zero level, or (iii) a sharp fall at about 1500 hrs LT (afternoon counter-electrojet) even below the zero level and a subsequent recovery to zero level by dusk, or (iv) occasionally a small positive excursion above zero level soon after or near dusk. The latitude dependences of all these are not alike from day to day; but in general the maxima show similar latitude dependences while the minima show more rapid decreases with latitude for the morning counter-electrojets and noontime fluctuations and less rapid decreases with latitude for the afternoon counter-electrojet. All these show generally a north-south asymmetry, southern magnitudes larger than the northern magnitudes; but the degree of asymmetry varies greatly from event to event. Also, the counter-electrojets may be centered occasionally 2-3° away from the dip equator.

(v) During storms, the magnitude of SSC is roughly the same at equatorial and non-equatorial latitudes if the SSC occurs during night. For SSC occurring during daytime, not only the first sudden impulse but even the whole of the initial phase may have enhanced magnitudes nearer equator, more so nearer noon hours. The electrojet may evolve smoothly as on quiet days or may show violent fluctuations. Some of these have similar latitude dependences and hence may be reflecting modulations in the strength of a single electrojet current strip. However, quite often the minima as also the morning and/or evening counter-electrojets show latitude dependence patterns quite different from those for the maxima. Thus, reverse currents having different centerings and/or latitude dependence profiles seem to be occurring simultaneously with the normal currents, probably at different altitudes. During the main phase, the depressions at 0° dip are sometimes much larger than those at ± 5° dip but during daylight hours only, thus indicating strong reverse currents at equator. Patterns at different longitudes could be similar or radically different.

It would seem from this analysis that the current structure in the electrojet region is highly complex. Not only does it change in magnitude and position from hour to hour and day to day but there seems the possibility of multiple current systems which obviously can be only at different altitudes. If these are caused by peculiar neutral winds as for example envisaged in the model of Richmond,²⁰⁻²¹ these winds must be very complex indeed. It would be necessary then to find some way of observing these winds and explain their complex behaviour. It is hoped that simultaneous observations with vhf backscatter radar and/or rocket flights at well-chosen occasions would throw more light on this baffling behaviour of the equatorial electrojet. The recent report by Carter et al.⁷ that layers having oppositely directed drift velocities were observed within a few km of each other in the E-region is of great significance in this connection. Copious observations on similar lines would be very valuable.

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