Geomagnetic S_q Variations and Parameters of the Indian Electrojet for 1958, 1959

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ABSTRACT. Geomagnetic S_q variations at Trivandrum, Annamalainagar (both close to the magnetic equator) and Alibag are examined for the different seasons for the years 1958 and 1959. The ranges in H for the observatories close to the magnetic equator are as usual very large. Maximum ranges in H and Z occur in the equinoctial months while maximum range in D occurs during the summer. Other characteristics of the variations are pointed out, especially the anomalous nature of S_q (Z) at Trivandrum and Annamalainagar.

Using the magnitudes of S_q (H) at the three observatories for the period April to August (a period during which the solar noon-zenith angle varies through about 20° for all the three observatories), estimates of the parameters of the Indian electrojet are made. The half-width of the electrojet is found to be nearly 300 km. The total current strength in the electrojet is about 148 A/km or 16,000 A/degree latitude. The factor by which the normal S_q current strength is intensified at the magnetic equator is found to be 2·4.

1. Introduction

1·1. Geomagnetic S_q variations at Trivandrum and Annamalainagar, situated near the magnetic equator, have been examined by Yacob (1959) and Yacob and Pisharoty (1962) and shown to be large compared with variations at Alibag. Here the quiet-day variations in the different magnetic elements are studied for the years 1958 and 1959 to bring out the seasonal characteristics of the variations. From the magnitudes of the S_q (H) variations an attempt is made to estimate the width, the peak current intensity and the relative mean ionospheric conductivities of the day-time equatorial electrojet for the period under study.

1·2. The data used are from the magnetic observatories at Trivandrum, Annamalainagar and Alibag. The co-ordinates of these observatories and some of the relevant magnetic parameters at these observatories are given in Table 1.

2. S_q Variations

2·1. The mean S_q variations for the different seasons for the elements H, D and Z are shown in Figs. 1 and 2. The seasonal quiet-day ranges for the three observatories are given in Table 2.

2·2. The following are some of the striking features regarding S_q variations at these observatories—

(*a*) The ranges in S_q (H) are very large at the observatories close to the magnetic equator, *viz.*, Trivandrum and Annamalainagar compared to the range at Alibag.

(*b*) For all the observatories the ranges in S_q (H) and S_q (Z) are maximum during the equinoctial months but the range in S_q (D) is maximum during the summer months.

(*c*) The change in range for all the elements from the equinoctial months to summer months is appreciable for Trivandrum and Annamalainagar but not so for the northernmost observatory, Alibag.

(*d*) S_q (H) variations at all the three observatories are practically in phase in all the three seasons, the maxima occurring within a few minutes of each other. There is a clear tendency for maximum S_q (H) to occur earlier by about an hour in the equinoctial months, specially at Trivandrum and Annamalainagar.

TABLE 1

Observatory	Geographic		Geomagnetic		Magnetic latitude	Declination
	Lat.	Long.	Lat.	Long.		
Trivandrum	8° 29′N	76° 57′E	0° 54′S	146° 18′E	0° 19′S	—2° 57′
Annamalainagar	11° 22′N	79° 41′E	1° 32′N	149° 22′E	2° 42′N	—2° 48′
Alibag	18° 38′N	72° 52′E	9° 28′N	143° 36′E	12° 55′N	—0° 49′

TABLE 2

S_q Daily Ranges in H, D and Z at Trivandrum, Annamalainagar and Alibag

Observatory	H				D			Z		
	X	S	E	W	S	E	W	S	E	W
Trivandrum	136	136	175	124	36	23	18	45	58	46
Annamalainagar	104	105	132	94	47	36	13	40	54	36
Alibag	64	72	76	58	66	62	20	45	46	16

S for summer (May, Jun, Jul and Aug); E for Equinoxes (Mar, Apr, Sep and Oct); W for Winter (Jan, Feb, Nov and Dec); X for the months Apr to Aug [range from 0730 LMT to time of maximum S_q (H) for X only]

(*e*) S_q (D) at all the three observatories are practically in phase during the summer and equinoctial months. During the winter months the variations are not only much reduced in magnitude but for the earlier part of the day the phase is reverse of that seen for the other seasons, especially at Trivandrum and Annamalainagar. At any one station the variations are in phase for the summer and equinoctial months.

(*f*) S_q (Z) shows a certain amount of dissimilarity from one observatory to another. There is a general phase reversal in the variations between Trivandrum on one hand and Annamalainagar and Alibag on the other. This phase reversal appears to be confined to the day-time portion of the variation only. The day-time peak variation at Trivandrum occurs uniformly at 10^h LMT for all the seasons, at Annamalainagar at $13 \cdot 5^h$ LMT for the summer and winter and at 12^h LMT for the equinoctial period and at Alibag it occurs at about 11^h LMT uniformly for all the seasons. $S_q(Z)$ at Trivandrum and Annamalainagar in the winter months is of appreciable magnitude and comparable with S_q (Z) in summer while at Alibag the winter S_q (Z) is insignificantly small as was seen for S_q (D) in winter.

3. Parameters of the electrojet

3·1. The location of the three observatories both magnetically and geographically affords an excellent opportunity for arriving at estimates of the parameters of the day-time electrojet over south India. Trivandrum is only 35 km south of the magnetic equator, Annamalainagar is 297 km and Alibag is more than 1000 km north of magnetic equator. The maximum longitudinal separation among them is about 7° and latitudinal separation is about 10°. The difference in magnetic declination among the observatories is only about 2°. The magnetic north directions are thus about the same at the three observatories. As will be seen later, the effect of the electrojet over the region of the magnetic equator, which is postulated to account for the large S_q (H) variations near the equator, has negligible influence on S_q (H) at Alibag.

3·2. According to Baker and Martyn (1953) the electrojet is a result of the enhanced conductivity at and near the magnetic equator, resulting from the inhibition of Hall

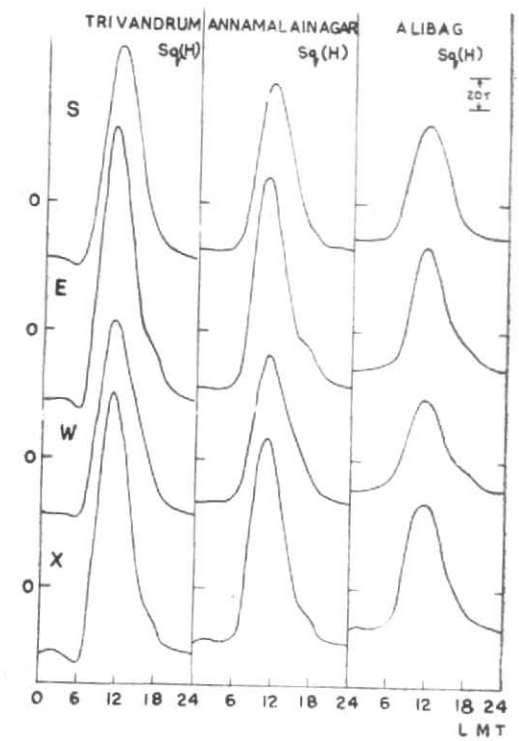

Fig. 1. Quiet-day variations $[S_q(H)]$ in the horizontal magnetic north component of the geomagnetic field at Trivandrum, Annamalainagar and Alibag for summer (S) [May, Jun, Jul and Aug], equinoxes (E) [Mar, Apr, Sep and Oct], winter (W) [Jan, Feb, Nov and Dec] and the period Apr to Aug (X) for the years 1958 and 1959

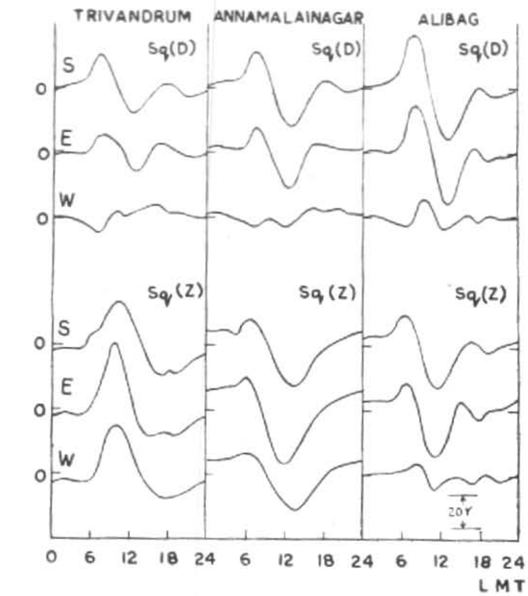

Fig. 2. Quiet-day variations of the magnetic east component $[S_q(D)]$ and the vertical component $[S_q(Z)]$ of the geomagnetic field at Trivandrum, Annamalainagar and Alibag for summer (S) [May, Jun, Jul and Aug], equinoxes (E) [Mar, Apr, Sep and Oct], winter (W) [Jan, Feb, Nov and Dec] for the years 1958 and 1959

currents. The current strength in the region of the magnetic equator can be represented as

$$I = E\ (\sigma_1 + \sigma_2{}^2/\sigma_1) \tag{1}$$

where E is the electric field, σ_1 the Pedersen conductivity or the conductivity transverse to the magnetic field and σ_2 the Hall conductivity, transverse to both the magnetic field and the electric field. Thus $i_1 = E\sigma_1$. is the mean strength of the extensive (latitudinally) ionospheric currents and $i_2 = E \times (\sigma_2{}^2/\sigma_1)$, the mean enhancement of the strength in the electrojet belt over the magnetic equator. The effect in H at any place below these current sheets will be given by $2\pi i_1 + 2\phi i_2$, where ϕ (in radians) is the angle subtended by the electrojet belt at the place. Alibag being quite distant from the magnetic equator, ϕ becomes negligible and, therefore, the electrojet belt will have no significant contribution to the effect in H there.

3. 3. The horizontal and vertical components of the field (in oersted) due to the current of strength i_2 (e.m.u./cm) in a belt of half-width w cm and height from ground h cm at a latitudinal distance d cm from the projection on the ground of the centre of the belt are given by

$$\triangle H = 2i_2\left\{\tan^{-1}\frac{d+w}{h} - \tan^{-1}\frac{d-w}{h}\right\} \tag{2}$$

$$\triangle Z = 2i_2 \ln\left\{\frac{h^2 + (d+w)^2}{h^2 + (d-w)^2}\right\}^{\frac{1}{2}} \tag{3}$$

If the distances of two observatories from the projection on the ground of the centre of the electrojet belt is known, then the ratio of the effect in H at these observatories will depend only on the width of the belt when h is constant. From a plot of such ratios for different half-widths of the electrojet belt, the actual width of the belt may be picked up if the ratio of observed effects, due to i_2, at the two places is known.

3·4. In the case of Trivandrum and Annamalainagar we know their distances from the magnetic equator. These distances can be taken as the distances from the mid-point of the electrojet, provided that the mid-point of the electrojet coincides with the magnetic equator. Theoretical considerations (Baker and Martyn 1953) show that the electrojet should be centred at the magnetic equator where the magnetic dip is zero and the inhibition of Hall currents is maximum. Observations at Nigeria (Onwumechilli 1959) show a shift of about 0·5° of the mid-point of the electrojet from the magnetic equator. Forbush and Casaverde (1961) find the electrojet near Huancayo in South America to be centred at the magnetic equator. Osborne (1962) finds only a few km difference between the mean axis of the electrojet and the magnetic equator. For the purpose of the present investigation, it will be assumed that the electrojet is centred at the magnetic equator. Any effects that may arise from small shifts between the magnetic equator and the centre of the electrojet will be discussed later.

3·5. Baker and Martyn (1953) find the total effective conductivity $[\sigma_3=\sigma_1+(\sigma_2^2/\sigma_1)]$ of the S_q current layer at the magnetic equator to be greatest at the height of 100 km. In the absence of any reliable method of estimating the height of the Indian electrojet, it will be assumed to be located at 100 km. Taking the distance of Trivandrum from the projection on the ground of the centre of the electrojet to be 35 km and that of Annamalainagar 297 km, the ratios of the electrojet effect ($\triangle H$) at a distance of 35 km to that at a distance of 297 km are computed for different half-widths of the electrojet and a curve of the ratio *versus* half-width is drawn as shown in Fig. 3. In order to pick up from this curve, the actual width of the electrojet belt prevailing for the period of the investigation, the observed ratio of the electrojet effects due to the portion of the current i_2, at Trivandrum and Annamalainagar has to be found.

3·6. Alibag is at such a distance from the magnetic equator that the electrojet effect becomes negligible there (Ref. Fig. 4) The $S_q(H)$ range there may be taken to be entirely due to the normal S_q currents. Assuming this normal $S_q(H)$ range to be about the same in the region between Alibag and Trivandrum, we may proceed to eliminate this normal range from the actual ranges at Trivandrum and Annamalainagar and take the residuals as the effects due to the current i_2 in the electrojet and proceed to find the ratio of these effects. If, for this purpose the daily $S_q(H)$ ranges are considered, the effect of the night-time part of S_q current-circuit (Chapman and Bartels 1940) will also be present and obviously the parameters of the electrojet deduced will be of larger magnitude to the extent of the effect of the night-time S_q currents. In order to eliminate, as far as possible, the effect of the night-time currents, range should be confined to the day-time, preferably the time, T, when the western portion of the W-E S_q currents comes over the station, and the time, T_m, when S_q (H) is maximum. For all practical purposes the time T, may be taken to correspond to the time when S_q (D) is maximum. Fig. 2 shows that T for all the stations for summer and equinoctial months is 0730 LMT. Thus for the purpose of estimating the electrojet parameters, $S_q(H)$ ranges are determined from 0730 to T_m LMT.

3·7. A pertinent uncertainty is involved in the assumption that S_q (H) range at Alibag is representative of the normal S_q (H) range for the entire region between Alibag and Trivandrum. But the error involved will be much reduced if the mean S_q (H) range is taken for a period of the year during which

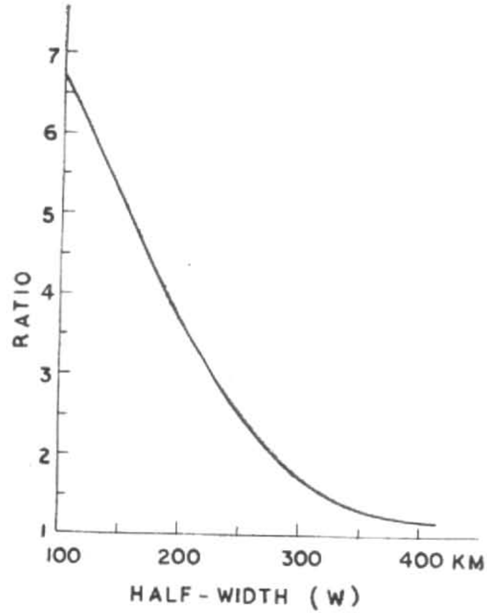

Fig. 3. Plot of half-width, w, of the electrojet against the ratio of the effect due to the electrojet portion i_2 of the current in the electrojet belt at Trivandrum (distance 35 km from the magnetic equator) to that at Annamalainagar (distance 297 km from the magnetic equator)

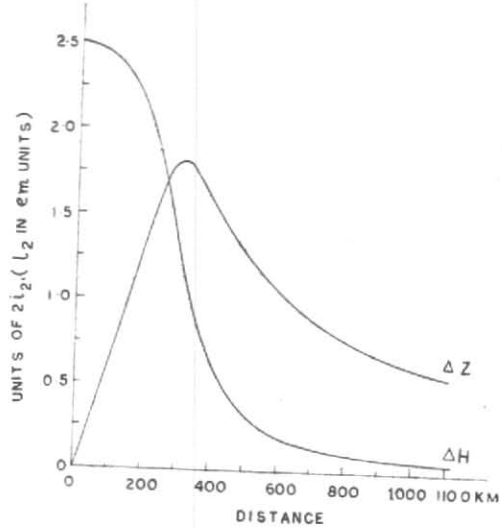

Fig. 4. Variations, with distance from the projection on the ground of the central axis of the electrojet, of the horizontal ($\triangle H$) and the vertical ($\triangle Z$) components of the magnetic field due to an electrojet belt of the half-width 300×10^5 cm at a height of 100×10^5 cm from ground and with a current strength of i_2 e.m.u./cm

For places to the north of the central axis of the electrojet (with current in the W-E direction), $\triangle H$ is positive (northward) but $\triangle Z$ is negative (upward). For places to the south of the central axis $\triangle H$ is positive and $\triangle Z$ is also positive (downward).

solar noon-zenith angle varies through the same range for all the three observatories, so that the effects arising from tidal forces and ionization intensities in the ionosphere at the three observatories become more or less equal. Such a period for Trivandrum, Annamalainagar and Alibag is roughly the months April to August (both inclusive), in which period the solar noon-zenith angle for each observatory executes (not simultaneously for the three observatories) an oscillation through a range of about 20°. $S_q(H)$ variation for this period is also shown in Fig. 1. Another method of determining the normal $S_q(H)$ ranges at the different observatories is to use Onwumechilli's (1959) equation

$$N = a\ (900 - L^2) \qquad (4)$$

where N is the normal range, L is geographic latitude and a a constant. The electrojet having no effect at Alibag, the S_q (H) range there can be equated to N and the constant a may be determined and then N for Trivandrum and Annamalainagar may be determined. But it is felt that, since this relation is based on data compiled by Vestine *et al.* for the years 1922-1933, which has very little relevance to the region under consideration, it may not be suitable for the purpose. In fact examination showed that it was so. Hence for the purpose of this investigation the $S_q(H)$ range at Alibag is considered as the normal range in the entire region between Trivandrum and Alibag.

3·8. In Table 2 are also given the $S_q(H)$ ranges between the times 0730 LMT and the time when S_q (H) is maximum (about 1100 LMT) for the three stations for the period April to August 1958-59. The effects at Trivandrum and Annamalainagar due to the enhancement of current strength by i_2 in the electrojet belt, are obtained by subtracting the range at Alibag from the ranges at these stations. The ratio of the residual range at Trivandrum to that at Annamalainagar is found to be 1·80. For this ratio the half-width of the electrojet is seen to be 290 km (Fig. 3), which for all practical purposes may be taken to be 300 km.

3·9. Taking the half-width of the electrojet to be 300 km and its height 100 km and supposing the electrojet to be centred at the magnetic equator, the horizontal component $\triangle H$ and the vertical component $\triangle Z$ of the magnetic field produced by the electrojet at different distances from the magnetic equator are computed with equations (2) and (3) and shown in Fig. 4. The unit of field for both H and Z is $2i_2$ (i_2 in e.m.u.). The horizontal component of the field produced at Trivandrum (distance 35 km from the magnetic equator) by the electrojet of current intensity i_2 is picked up from the curve $\triangle H$ of Fig. 4 as $2i_2 \times 2 \cdot 488$ e.m.u. This must be the same as the excess of $S_q(H)$ range (between the times T and T_m) at Trivandrum over that at Alibag for the period April to August 1958, 1959, which is $(72 \times 0 \cdot 6)\, \gamma$, (4/10 of the range is taken to be due to contributions from currents within the earth). The enhancement of current intensity in the day-time electrojet belt over the magnetic equator then works out to 87 amperes/km or 9570 amperes/degree latitude. The normal W-E S_q current intensity can be obtained with the assumption already made that its effect in the horizontal component is the S_q (H) range at Alibag, *viz.*, 64γ. Thus for the period under consideration $2\pi i_1 = (64 \times 0 \cdot 6)\gamma$ and, therefore, $i_1 = 61$ amperes/km or 6710 amperes/degree latitude. The total W-E current intensity in the electrojet belt is given by $i = i_1 + i_2$ and is of the value 148 amperes/km or 16,280 amperes/degree latitude. These estimates of current strengths hold good for the time of peak $S_q\,(H)$ variations for the period April to August 1958, 1959.

3·10. The relative ionospheric mean conductivities in the region of the electrojet belt may be estimated with equation (1). It is easy to see that σ_2/σ_1 is given by $\sqrt{i_2/i_1}$. From magnitudes of current strengths, i_1 and i_2, already arrived at in para 3·9 it is found that $\sigma_2 = 1 \cdot 2\sigma_1$. The relative magnitude of the total effective conductivity σ_3 [equal to $\sigma_1 + (\sigma_2^2/\sigma_1)$] is found to be $2 \cdot 4\ \sigma_1$. The factor by which the normal current strength is enhanced to give the total electrojet current strength is thus 2·4.

4. Discussion

4.1. The half-width of the Indian electrojet arrived at in para 3·8 for the period April to August 1958, 1959, *viz.*, 290 km is comparable with the value of 220 km given by Onwumechilli (1959) for the African electrojet for the period Dec-Jan 1956-57. Forbush and Casaverde (1961) found the half-width of South American electrojet, for the period 1957-1959, to be 330 km. Pisharoty and Srinivasan (1962) have estimated the half-width of the Indian electrojet for the period 1952-53 to be about 110 km. It is apparent that the width of the electrojet is not constant through the solar cycle but is wider during the period of high solar activity and much narrower during the period of low solar activity. In fact this has been pointed out by Kapadia (1962), who estimates the extent of the equatorial electrojet as reaching up to $\pm 7°$dip-latitude at solar maximum epoch and up to $\pm$ 5° dip-latitude during the minimum epoch.

4.2. The magnitudes of the total current strength i of the electrojet belt as well as normal current strength i_1 obtained in para 3·9 appear to be much higher than those given by Onwumechilli (1959) for an electrojet of half-width 220 km at a height of 100 km. His figure for i_2 is 6670 amperes/degree latitude and for i_1 is 3500 amperes/degree latitude (as estimated by Chapman). Onwumechilli's estimates pertain to the winter season and to a solar epoch (1956-57) somewhat less active than the period investigated here, *viz.*, summer and epoch of peak solar activity. On the basis of the broad estimate of 3500 amperes/degree latitude for the normal current strength given by Chapman, Onwumechilli obtained a factor of 2·90 by which the normal current strength is enhanced in the electrojet belt. The factor obtained here is 2·4 which is between his estimate and that of Baker and Martyn, which is 1·87 (Onwumechilli 1959).

4.3. The estimates of current strengths arrived at will not alter by any appreciable amount if the height of the electrojet is taken to be 125 km instead of 100 km. If h=125 km, half-width of the Indian electrojet turns out to be 280 km, which is only 10 km less than the half-width for h=100 km. The magnitudes of the current strength will increase only by about 1/15 of the estimated values.

4.4. The error involved in the estimates of the current strengths by the assumption that the magnetic equator coincides with the centre of the electrojet can be examined by giving a shift of 35 km (distance of Trivandrum from the magnetic equator) to the south and then to the north of the magnetic equator. In the first case Trivandrum will coincide with the projection on the ground of the centre of the electrojet while Annamalainagar will be 332 km from it. In the second case Trivandrum will be 70 km and Annamalainagar 262 km. Computation shows that for the first case the half-width of the electrojet will change to 330 km and the estimated total current strength of the electrojet belt will decrease by 1/70 of the estimated values. In the second case the half-width will be 260 km and the estimated current strength will increase by 1/40 of the estimated values. It may thus be seen that no appreciable change in the estimated current strength occurs even if the separation between the magnetic equator and the centre of the electrojet is as much as 0·3°.

4·5. It is rather difficult to gauge the error involved in current strengths by the assumption that the $S_q(H)$ range at Alibag is representative for the entire region of south India. Since the period April to August has been so chosen as to minimise any differences in effects due to tidal forces and conductivities in the ionosphere (para 3·7) the error involved is not expected to be much. It is, however, realised that the error is negative and that the real current strength of the electrojet may be a little less than the estimated values.

4·6. Examination of the relative magnitudes of $S_q(H)$ at the different stations (Table 2) during the different seasons indicate that the half-width of the electrojet does not show any appreciable change from season to season. Of course the current strength in the electrojet belt will vary from season to season approximately in the order of changes in $S_q(H)$ ranges in the different seasons.

5. Anomalous position of $S_q(Z)$ with respect to the electrojet

Referring to Fig. 4 it may be seen that curve $\triangle Z$ which gives the change with distance from the magnetic equator of the vertical component of the field due to the equatorial electrojet (of half-width 300 km at a height of 100 km) does not fall off as rapidly as the $\triangle H$ curve, that $\triangle Z$ is zero at the magnetic equator and is maximum at a distance (a little over 300 km in this case) just after the edge of the electrojet. It is to be expected that the electrojet should contribute very little to $S_q(Z)$ at Trivandrum and produce the maximum effect at Annamalainagar. But actual observed values (Table 2) indicate that for all the seasons $S_q(Z)$ ranges are consistently a little higher at Trivandrum. The fact that there is a lag of a couple of hours between $S_q(H)$ and $S_q(Z)$ variations (Figs. 1 and 2) indicate that S_q (Z) variations, to a large extent, are influenced by the N-S and S-N branches of the S_q-currents in addition to the W-E branch and the electrojet and hence the influence of the electrojet in $S_q(Z)$ is not prominent. However, the general phase reversal—para 2·2(f)—between $S_q(Z)$ at Trivandrum on one hand and Annamalainagar and Alibag on the other, suggests that these variations are mainly due to the day-time W-E S_q currents as well as the electrojet. To account for the larger $S_q(Z)$ magnitude at Trivandrum it may be necessary to assume that the electrojet is situated about mid-way between

Trivandrum and Annamalainagar. But then this position of the electrojet will not conform to the differences in the observed $S_q(H)$ magnitudes at the two stations. A plausible cause of the apparent anomalous $S_q(Z)$ in the region may be due to differences in the internal conductivities. $S_q(Z)$ magnitudes contributed by induced currents within the earth being opposite to that contributed by external currents, the smaller range in $S_q(Z)$ at Annamalainagar than what it should be, when the effect of the electrojet is considered, indicate that internal conductivities at Annamalainagar are greater than that at Trivandrum. Computations with the order of the current strength of the electrojet arrived at earlier show that the internal conductivity at Annamalainagar should be greater than that at Trivandrum by a factor of 2·3. A factor for relative internal conduc ivities of this order for the two places will be expected to offset the differences in $S_q(H)$ magnitudes observed. It, therefore, appears that even this explanation is not tenable and that $S_q(Z)$ variation is an anomalous feature in the region.

6. Conclusion

Geomagnetic $S_q(H)$ variations at both Trivandrum and Annamalainagar, situated near the magnetic equator, for the different seasons of the solar peak activity period 1958, 1959 are very large compared with the variations at Alibag (magnetic dip-lat. 13°) which obviously point to the existence of concentrated currents (electrojet) in the narrow belt over the magnetic equator.

$S_q(H)$ and $S_q(Z)$ ranges at all the three observatories are maximum during the equinoctial months but $S_q(D)$ range is maximum during the summer months.

The following are the estimates of magnitudes of the parameters of the day-time equatorial electrojet as deduced from magnitudes of $S_q(H)$ at Trivandrum, Annamalainagar and Alibag for the period April to August 1958-1959—

(*a*) The half-width of the electrojet is about 300 km.

(*b*) The total mean current strength in the electrojet belt is about 16,000 amperes/degree latitude.

(*c*) The factor by which the electrojet current strength is enhanced over the normal S_q W-E current strength is 2·4.

$S_q(Z)$ magnitudes at Trivandrum and Annamalainagar do not appear to fit in with the location and other parameters of the equatorial electrojet as deduced from S_q (H) magnitudes at these stations.

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