Characteristic of Sq Current Based on Seasonal Variation in Different Phases of Solar Cycle

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***Abstract*—The ionospheric current (Sq) variation is changeable throughout a year. This study is aimed to examine the behavior of Sq variation in different phases of the solar cycle. The horizontal component has been used to measure the monthly diurnal variation, Sq (H) and MSq (H) based on seasonal variation. The magnetic data were extracted from magnetic data acquisition system (MAGDAS) situated at Langkawi station (Geog. Lon. 99.68◦E, Geog. Lat. 6.30◦N), Malaysia. The data were collected in 2008 and 2012 to represent a different phase of the solar cycle. The result of the numerical simulation indicates that the maximum amplitude of Sq (H) values were 72.96 nT and 115.16 nT in October 2008 and September 2012, respectively. Moreover, the Sq (H) variation was generally low during night time and oscillated between -21.54 nT and 5 nT for both years. The Sq (H) amplitude was high at low latitude, specific to equatorial region due to the superimposition of Sq and EEJ current. Furthermore, the active CEJ occurred within 06:00 LT to 18:00 LT. The higher magnitude of CEJ were -27.96 nT and -35.51 nT were observed in 2008 and 2012, respectively. Both maximum readings occurred in May around 06:00 LT – 07:00 LT was due to the consequence of late interchange process between nighttime westward current to daytime eastward current flow. The seasonal mean variation revealed the maximum of MSq (H) was 66.72 nT and 96.51 nT in 2008 and 2012, respectively. Both maxima values were peaked during Equinox season resulting from the strong dynamo process and great solar thermal heating with minimal loss rates other than, during Equinox, the Sun exists right above the equator line.**

***Index Terms*— ionospheric current, Sq current, Sq (H), MSq (H).**

I. INTRODUCTION

As state by (Campbell, 1989) the Solar Quiet (Sq) is a variation of geomagnetic field that excluded from any solar system disturbances. Sq variation is associated with the primary source currents at ionosphere specific at E region (90 – 150 km) altitude. The ionospheric conductivity is closely related to the Sq enhancement. It tends to rise up when there have an increasing of Sun activities, hence the total Sq also increased. The Sq current can be measured from the Earth surface by right it was included both sources which are an external and internal part. The Sq current is engaged by the ionospheric wind dynamo that is driven by thermal and wind tidal motion located at E region. Reference [1], has reviewed a relationship between Sq and Equatorial Electrojet (EEJ) that dominant current at equatorial region. The EEJ is eastward current flowing at magnetic dip equator in a daytime and the center located at the magnetic equator (latitude ±3˚). Based on Gauss law fundamental, Spherical Harmonic Analysis method was initiated that able to generate the optimum representation of the geomagnetic field. The previous finding by [2] used the SHA method to present the Sq variation that directly related to the external current source. This method is widely used in Nigeria [3], Australia [1] and India- Siberia region [4] continuously up to recent years in most of its objectives is to analyze the Sq current based on seasonal variation and to obtain the electrical conductivity-depth on that particular region. By referring the studies conducted at others region, the concept of SHA was successfully deploy and the Sq analysis manage to carry out at Malaysia region by using Langkawi station in 2008 and 2012 for the first time.

The aim of this study is to analyze the Sq variation of the geomagnetic field in 2008 and 2012 by considering solar minimum and solar maximum. The significant of this conducted studies is to understand the dynamic process of the ionospheric Sq current system focusing on Malaysia region. Plus, the different phases of solar cycle might contribute some similarity with other region as well. The Sq variation is extended to mean of Sq based on seasonal variation in order clarify the Sq current system depending to the season. This study only focuses on the horizontal geomagnetic data as a dominant component at equatorial region.

II. DATA AND ANALYSIS

The analysis has been used in this study is the hourly mean values of spherical coordinate H, D, and Z but the H component is dominant in the equatorial region. The geomagnetic data in 2008 and 2012 were extracted from the Magnetic Data Acquisition System (MAGDAS) Langkawi station (Geog. Lon. 99.68◦E, Geog. Lat. 6.30◦N).

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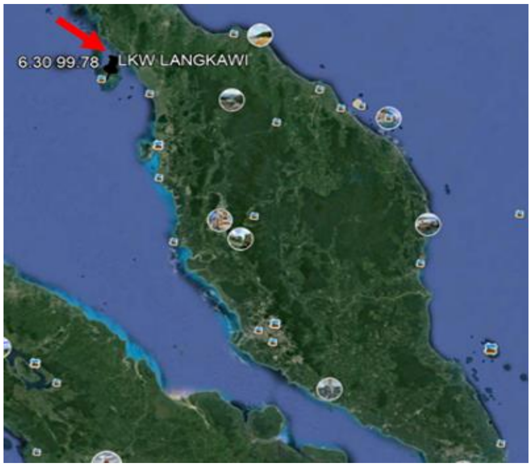

Fig. 1. Map showing locations, pointed at Langkawi station used in the analysis.

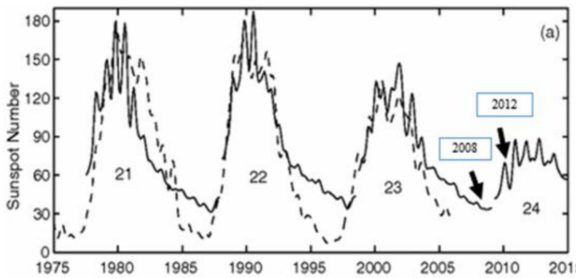

Fig. 2. The solar cycle 24 with marked the minimum and maximum phase of the solar cycle. [6]

III. METHODOLOGY

A. Spherical Harmonic Analysis

The method employed to obtain the objective of this study is Spherical Harmonic Analysis (SHA). This method was initiated using Gauss law. The ionospheric Sq current basically dependent on external and internal current source. The current separation required a converging series by Maxwell separable series solution in equation (1).

$$V = a\sum_{n=1}^{\infty}\left(\left(\frac{r}{a}\right)^{n} s_n^e + \left(\frac{r}{a}\right)^{n+1} s_n^i\right) \qquad (1)$$

Where;
Re ~ a is a radius of earth;
The radius term consists of rn and the second one is $(1/r)^n$. The first series of r as increases, the term becomes increasingly large so called as external which is current from the external source, meanwhile for a second series term of r as increases, the term becomes smaller and continuously keep smaller indicate the current is from the internal source. V is a summation of current from internal and external that contribute to geomagnetic variation.

Current from internal and external source expressed using Gauss spherical harmonic express as;

$$V_n^m = C + \sum_{n=1}^{\infty}\sum_{m=0}^{n} \{(a_n^{me} (\tfrac{r}{a})^n + a_n^{mi} (\tfrac{a}{r})^{n+1}) \cos(m\theta) + (b_n^{me} (\tfrac{r}{a})^n \, b_n^{mi} \left(\tfrac{a}{r}\right)^{n+1}) \sin(m\theta) \} P_n^m (\theta) \qquad (2)$$

Where;
C: Constant of integration
a: Geocentric distance
θ: Geomagnetic co-latitude
r: Earth's radius
φ: Local time of geomagnetic observatory

$m_n^{me}, m_n^{mi}, b_n^{me}, b_n^{mi}$ represent Legendre polynomial coefficient where *e* and *i* represent external and internal respectively.

$P_n^m(\theta)$ is Legendre polynomial function of co-latitude θ only

n: degree *m*: order

Where;
Value of *n* must be 1 or greater, *m* is always less than or equal to *n*.
Schmidt Legendre polynomial referred Campbell 1997, the function can be computed as;

$$R_n^m = \sqrt{n^2 - m^2}\, P_0^0 = \cos(\theta); P_1^1 = \sin(\theta) \qquad (3)$$

$$P_n^m = \sqrt{\frac{2m-1}{2m}}\, ; \sin(\theta)\, P_{m-1}^{m-1}{}_{;\ for\ m>1, n=m} \qquad (4)$$

$$P_n^m = \frac{(2n-1)\cos\theta\ P_{n-1}^m - R_{n-1}^m - P_{n-2}^m}{R_n^m}\ for\ n > m \qquad (5)$$

$$\frac{dP_n^m}{d\theta} = \frac{n\cos\theta P_n^m - R_n^m - P_{n-1}^m}{\sin\theta} (except\ for\ \theta = 0\ or\ 180°) \qquad (6)$$

Equation 6 is undefined at poles (i.e $\theta = 0\ 0r\ 180°$)

For Sq analysis, the geocentric distance approximately equal to radius of earth ($a \approx r$).
Taking;

$$a_n^{me} + a_n^{mi} = A_n^m$$
$$b_n^{me} + b_n^{mi} = B_n^m$$

Referred Campbell 1997, the harmonic series simplification from equation (2) as;

$$V_n^m(\theta,\varphi) = R_e + \sum_{n=1}^{\infty}\sum_{m=0}[A_n^m\cos(m\varphi) + B_n^m\sin(m\varphi)]\,P_n^m(\theta) \quad (7)$$

$a_{n,}^m\ b_n^m, c_n^m, d_n^m$ For m>0 calculated as intermediate coefficient, and expressed as;

$$a_n^m = \frac{2n+1}{4n\,(n+1)}\int_0^{180}\left[X_c^m\frac{dP_n^m}{d\theta}\sin\theta + Y_c^m\, m\, P_n^m\right]d\theta \quad (8)$$

$$b_n^m = \frac{2n+1}{4n\,(n+1)}\int_0^{180}\left[X_s^m\,\frac{dP_n^m}{d\theta} + Y_c^m\, m\, P_n^m\right]d\theta \quad (9)$$

$$c_n^m = \frac{2n+1}{4}\int_0^{180} Z_c^m P_n^m\sin(\theta)\,d\theta\ but\ if\ m = 0, c_n^0 = 2c_n^m \quad (10)$$

$$d_n^m = \frac{2n+1}{4}\int_0^{180} Z_s^m P_n^m\ \sin(\theta)\,d\theta \quad (11)$$

The integral for above equation is a summation over the ranging from (0° to 180°). The infinite increments have been used in this study is 2.5 step to compute the intermediate value. This increment is selected to be appropriated to the wavelength resolution that is to be accomplished by SHA fitting.

Legendre polynomial coefficient equation as;

$$a_n^m = \frac{(n+1)a_n^m + c_n^m}{2n+1};\ a_n^{mi} = \frac{na_n^m - c_n^m}{2n+1} \quad (12)$$

$$b_n^{me} = \frac{(n+1)b_n^m + d_n^m}{2n+1};\ b_n^{mi} = \frac{nb_n^m - d_n^m}{2n+1} \quad (13)$$

The geomagnetic dataset which consists of 5 min averages has successfully obtained the value of Sq (H) referring this establish a method. The analysis is continued to calculate the mean of Sq (H) variation based on seasonal variation (D- Solstice, Equinox, and J-Solstice). A simple average calculation express as;

$$H_{0=}\frac{H_1 + H_2 + H_3 + H_4}{4} \quad (14)$$

Langkawi station located above the focus of the equatorial electrojet. This analysis has been done without removing the influence of equatorial electrojet (EEJ) current.

IV. RESULT AND DISCUSSION

A. Monthly Diurnal Variation

Fig. 3 shows the monthly mean diurnal variation of Sq (H) observed at Langkawi, Malaysia from January to December for the years in 2008 and 2012. The colored curves correlate to different years where the blue curve represents 2008 data and the red curve is represent 2012 data. The period of this study is during the solar cycle 24 where 2008 and 2012 are during minimum and peak solar cycle respectively. The maximum Sq (H) for the years is 72.96 nT in 2008 and 115.2 nT in 2012. There is also a lack of data in 2008 during the month of March, August and September due to unavailable data during this period. The Sq (H) variation is generally low during night time and oscillates between -21.54 nT and 5 nT. The Sq (H) has been shown a few characterization during daytime;

Sq (H) is mainly positive for January to December and it was observed the maximum is around 12:00 local time. The research study by [7] and [8] also found the maximum of Sq amplitude reaches around 12:00 in local time. In addition, according to [9, 10, 11 and 12] are expressly said the Sq amplitude is very dependent on local time and the strength of Sq is boosted in the equatorial region. Continuous researched by the previous author found the maximum Sq amplitude is varied from 10:00 LT to 12:00 LT in the equatorial region. This is explained by [7], the maximum of Sq frequently peak within 10:00 LT – 12:00 LT is due to high solar activity, resulting in the plasma at upper atmosphere more conductive in the long period until it reaches a peak at 12:00 LT. The observations by [10] stated the Sq (H) amplitude is frequently maximum at 11:00 during the minimum solar cycle. As can be seen, the maximum of Sq (H) is around 12:00 LT in 2012 (red curves) meanwhile the maximum of Sq (H) is around 11:00 LT in 2008 (blue curves). This finding is also consistent with past studies by [7-12].

Sq (H) amplitude is high at low latitude, specific to equatorial region due to the combination of Sq and EEJ current. The combination of Sq and EEJ is enhanced and amplified the current around the EEJ phenomenon zone. This statement was mentioned by [13] where the Sq amplitude reaches a maximum persistently at EEJ zone. The EEJ is caused by many factors. The major cause of EEJ is the enhanced zonal ionospheric conductivity in the equatorial region. This process so-called cowling conductivity [14, 15]. Reference [16] found the magnetic equator is the center of EEJ. The EEJ current is originally separated from Sq since the driving mechanism is distinctively different. The Sq is driven by ionospheric wind dynamo meanwhile EEJ is driven by a solar-wind magnetospheric dynamo. Sq current is solar activity dependence. The important feature of solar activity is the occurrence of EEJ and CEJ. As shown in Fig. 1, CEJ is represented by the Sq (H) variation goes below than the baseline [17]. The baseline has been set to be zero. The active CEJ occur within 06:00 LT to 18:00 LT. The higher magnitude of CEJ is around -27.96 nT observed in 2008 and -35.51 nT observed in 2012. Both maximum readings occur in May around 06:00 LT – 07:00 LT is due to the consequence of late interchange process between nighttime westward current to daytime eastward current flow.

The amplitude of Sq (H) is higher before midnight compared to before sunrise hours [17]. In 2008, the maximum Sq (H) is 72.96 nT and 115.2 nT in 2012. Both maximum readings occur in September and October, where the maximum intensity of current generally occur in March, April, September, and October which is Equinox season. Based on [14-17], the amplitude Sq (H) is minimum at that moment due to the low conductivity, low ionospheric conductivity and low neutral wind before midnight and sunrise hours. The absence of the solar thermal heating process became the main factor of the behavior Sq (H) changeable. As concluded, the amplitude of Sq (H) at the equatorial region is influenced by different mechanism during daytime and nighttime. The ionospheric conductivity more influenced in daytime meanwhile the conductivity distribution of Earth structure is dominant during nighttime.

B. *Seasonal Variations*

The maximum reading of Sq (H) and MSq (H) amplitude have been put on the table so that it can be easily identified. All seasonal peak around 12:00 LT with highest Sq (H) amplitude of (72.96 nT) in 2008 and (115.2 nT) in 2012. It was identified occur during Equinox season. D- Solstice get the lowest reading compared to Equinox and J- Solstice season. Since the seasonal varies maximum during Equinox and minimum during solstice month, its shows a semiannual variation. But, the annual variation analysis is not detailed in the analysis as the process is dominant at high and middle latitude. This restriction was required to make sure the analysis is manageable. Semi-annual variation is closely related to the increment of Sq amplitude at low latitude and equatorial latitude within Equinox months. It may cause a strong EEJ current exist during that season. The highest intensity of MSq (H) during equinox results from strong dynamo process and great solar thermal heating with minimal loss rates other than during Equinox, the Sun is existed locate right above the equator line. The values of MSqH were observed are maxima around noon, 12:00 LT, seen in 2008 (~66.72 nT) and (~96.51 nT) seen in 2012. The characteristic of the highest Sq (H) and MSq (H) in the line of the previous finding and agreeable with [9-13]. The results obtained highlight the finding;

The positive reading consistently in the daytime, and switch to negative reading in the night time. Same goes for all three season. The current flowing in night time either west or east direction may involve a physical process and may lead to strong current induction occur at Langkawi station. Based on two years data, 2008 and 2012 which represent a different phase of the solar cycle, it can be concluded, the amplitude of Sq (H) during the minimum solar cycle is lower than the amplitude of Sq (H) during peak solar cycle. This phenomenon is mainly referred to minimum solar activity during the minimum solar cycle and contrariwise during the maximum solar cycle.

V. Conclusion

The Sq current of the horizontal component at the Langkawi station for 2008 and 2012 has been extracted from Magnetic Data Acquisition System (MAGDAS) by the application of Spherical Harmonic Analysis (SHA) approached. From the result obtained, it was summarized as;

(1) The Sq (H) value at Langkawi station was included by Equatorial Electrojet (EEJ) current. It was mentioned earlier that the EEJ influenced are not removing in this study.

(2) The Sq intensity is maximum during Equinox and minimum during D solstice considering that the Sun exists right above the equator during equinox season.

(3) The Sq intensity is much higher in 2012 compared to 2008 considering that the Earth experience more solar activity during the solar maximum phase, 2012.

(4) The Sq intensity peak around noon, 12:00 LT during solar maximum and peak around 11:00LT during solar minimum.

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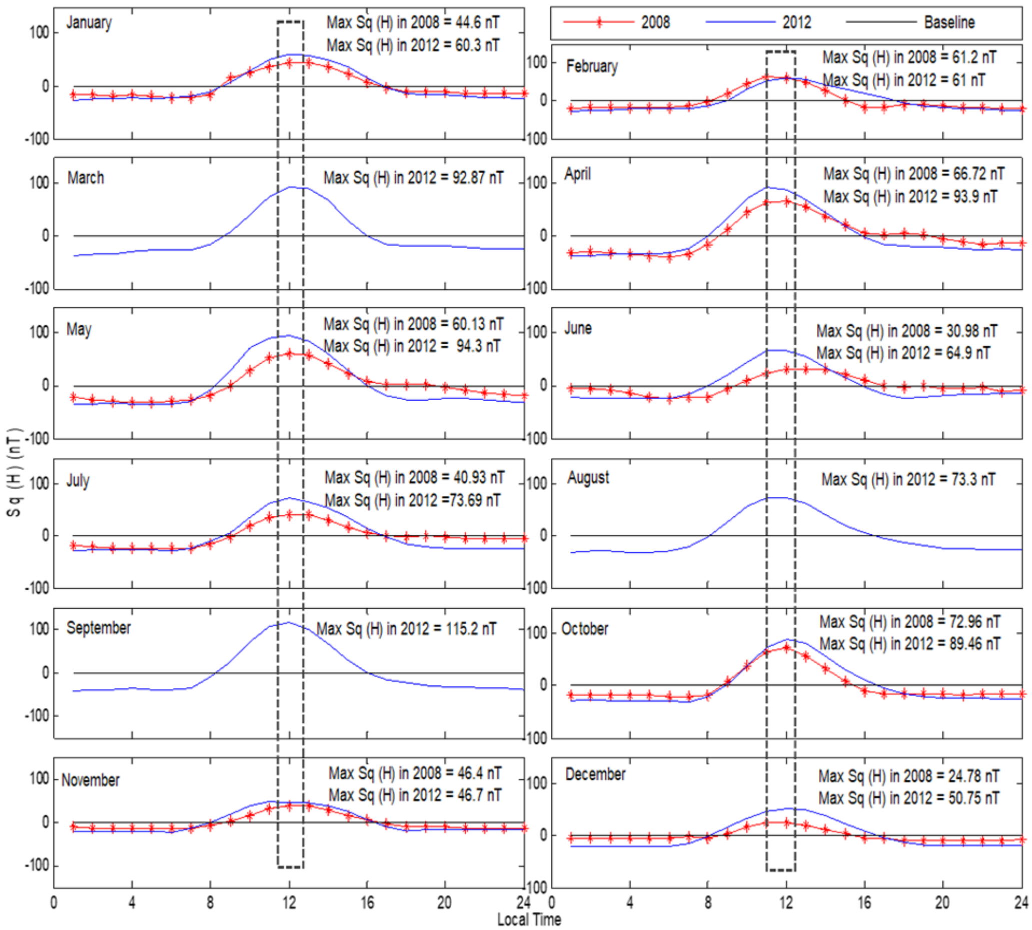

Fig.3. The average of Sq (H) in 2008 (red curve) and 2012 (blue curve). It was attached to the maximum and the minimum value of Sq (H) for both years. The maximum Sq (H) is 115.2 nT in 2012 and 72.96 nT in 2008. Both maximum peaked during Equinox season. The maximum reading randomly peaked at 12:00 LT.

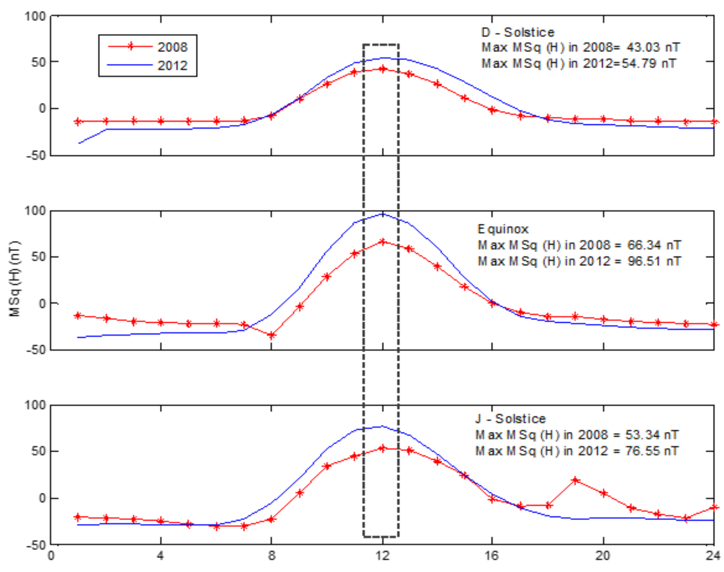

Fig. 4. the mean of Sq amplitude, MSq (H) was illustrated based on seasonal variation. The maximum value is during Equinox season as presented. The MSq (H) is maximum during Equinox for both years with 66.34 nT for 2008 and 96.51 nT for 2012.

TABLE I
THE MAXIMUM AND MINIMUM VALUE OF SQ (H) IN 2008 AND 2012.

	2008	2012
Max Sq (H)	72.96 nT (October)	115.2 nT (September)
Min Sq (H)	24.78 nT (December)	47.4 nT (November)

TABLE II
THE MAXIMUM AND MINIMUM VALUE OF MSQ (H) IN 2008 AND 2012 BASED ON SEASONAL VARIATION.

	2008	2012
MSq (H) – D Solstice	45.3 nT	54.79 nT
MSq (H) - Equinox	66.72nT	96.51 nT
MSq (H) – J Solstice	60.13 nT	76.55 nT

REFERENCES

[1] Yamazaki, Y., & Maute, A. (2017). Sq and EEJ—A review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. Space Science Reviews, 206(1-4), 299-405.

[2] Turner, J. P. R., Winch, D. E., Ivers, D. J., & Stening, R. J. (2007, November). Regular daily variations in satellite magnetic total intensity data. In Annales Geophysicae (Vol. 25, No. 10, pp. 2167-2174).

[3] Obiora, D. N., Okeke, F. N., & Yumoto, K. (2013). Determination of the crust-mantle electrical conductivity-depth structure of Niger Delta using solar quiet day (Sq) current. International Journal of Physical Sciences, 8(7), 272-276.

[4] Obiekezie, T. N., & Okeke, F. N. (2010). Upper mantle electrical conductivity results from the dip equator latitudes of West African region. International Journal of Physical Sciences, 5(6), 637-641.

[5] Yumoto, K. (2007). Space weather activities at SERC for IHY: MAGDAS. Bulletin of the Astronomical Society of India, 35(4).

[6] Choudhuri, A. R., Chatterjee, P., & Jiang, J. (2007). Predicting solar cycle 24 with a solar dynamo model. Physical review letters, 98(13), 131103.

[7] Onwumechili, C.A. (1960) Fluctuations in the Geomagnetic Field near the Magnetic Equator. Journal of Atmospheric and Terrestrial Physics, 17, 286-294. https://doi.org/10.1016/0021-9169 (60)90141-0

[8] Matsushita, S. (1969) Dynamo Currents, Winds, and Electric Fields. Radio Science, 4, 771. https://doi.org/10.1029/RS004i009p00771

[9] Bartels, J., & Johnston, H. F. (1940). Geomagnetic tides in horizontal intensity at Huancayo. Journal of Geophysical Research, 45(3), 269-308.

[10] Rastogi, R. G. (1974). Westward equatorial electrojet during daytime hours. *Journal of Geophysical Research*, *79*(10), 1503-1512.

[11] F.N. Okeke, Y. Hamano, Earth Planets Space 52, 237–243 (2000)

[12] Rabiu, A. B., Nagarajan, N., Okeke, F. N., Ariyibi, E. A., Olayanju, G. M., Joshua, E. O., & Chukwuma, V. U. (2007). A study of day to day variability in geomagnetic field variations at the electrojet zone of Addis Ababa, East Africa. *AJST*, *8*(2), 55.

[13] Abbas, M., et al. (2012) Variability of Electrojet Strength along the Magnetic Equator using MAGDAS/CPMN Data. Journal of Information and Data Management, 1, 10-13.

[14] Onwumechili, C.A. (1997) The Equatorial Electrojet. Gordon and Breach Science Publishers, Amsterdam, 627.

[15] Forbes, J.M. (1981) The Equatorial Electrojet. Reviews of Geophysics and Space Physics, 19, 469-504. https://doi.org/10.1029/RG019i003p00469

[16] H. Lühr, S. Maus, M. Rother, Noon-time equatorial electrojet: Its spatial features as determined by the CHAMP satellite. J. Geophys. Res. 109, A01306 (2004). Doi: 10.1029/2002JA009656

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