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Quiet Time Geomagnetic Field Variations in the Equatorial East African Region During the Inclining Phase of Solar Cycle 24

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Abstract: In the present paper, geomagnetic field data obtained from magnetometer measurements at two ground based stations have been used to study solar activity dependence of the solar quiet variations. The study has focused on the horizontal component of the geomagnetic field. The data used in the current study was obtained for all quiet periods from the solar minimum year (2009) through the solar maximum year (2014) to the start of the declining phase (year 2015) of Solar Cycle 24. The present study uses the magnetic data from International Real-time Magnetic Observatory Network (INTERMAGNET) station at Addis Ababa (geomagnetic latitude 0.18°N, geomagnetic longitude110.47°E) and MAGnetic Data Acquisition System (MAGDAS) station at Nairobi (geomagnetic latitude 10.65°S, geomagnetic longitude 108.18°E). The amplitude of mean *Sq(H)* has shown a dependence on local time of the day and solar activity, with peak values occurring between 1100 LT and 1200 LT and increasing with increase in solar activity; attaining highest values during the solar maximum year. Further, the amplitude of mean *Sq(H)* at Nairobi is higher than the corresponding values at Addis Ababa in the morning hours around 0700-0800 LT. The local time dependence is attributed to the variation in solar heating and ionization rates while the solar activity dependence is attributed to the increase in electron density with increase in solar activity. The larger morning hours' amplitudes at Nairobi than Addis Ababa are possibly due to counter electrojet effects close to the geomagnetic equator.

Keywords: Geomagnetic Field, Solar Quiet, Solar Activity

1. Introduction

Ions and to a lesser degree, electrons in the E-region of the ionosphere are coupled to the neutral components of the atmosphere; hence follow their dynamics. Atmospheric winds and tidal oscillations of the atmosphere force the E-region ion component to move across the magnetic field lines, while electrons move much slower at right angles to both the field and neutral wind (Baumjohann and Treumann, 1996). This relative movement constitutes an electric current and the separation of charge produces an electric field which in turn affects the current. The relation between conductivity σ , electric field, $\vec{E}$ and neutral wind velocity, $\vec{v}_n$, is

obtained by adding an electric field term $\vec{v}_n \times \vec{B}$ to the Ohm's law equation to write

$$\vec{J} = \sigma . \left(\vec{E} + \vec{v}_n \times \vec{B} \right) \qquad (1)$$

For mid and low latitude dynamo currents, the dominant driving force is the $\vec{v}_n \times \vec{B}$ electric field induced by ion motion across the magnetic field. The current system created by the tidal motion is called solar quiet or Sq . The Sq currents which create a disturbance on the magnetic field can be estimated on the ground by magnetometers and allows the determination of the strength of the currents. In accordance

with the contrast between day and night equatorial E-region electron densities, the *Sq* currents are concentrated in the dayside region. Matsushita and Maeda (1965) explain that *Sq* can be estimated by selecting quiet days from each month, eliminating the effect caused by lunar variation field and excluding non cyclic variation. The *Sq* field varies slowly in amplitude and phase through the months of the year (Campbell, 2003).

A number of studies of *Sq* variations have been carried out within the African sector. For example, Rabiu (2001) did a comprehensive study of the daily *Sq.* variations in the geomagnetic field for the entire solar cycle 22 (1986-1996) in middle latitude regions in the northern hemisphere. The *Sq* seasonal variation was maximum in June solstice and minimum in December solstice. Rabiu *et al.* (2007a) examined the variability of equatorial ionosphere by using ground based geomagnetic field data of H and Z obtained at the equatorial station of Ibadan. The results showed that the values of *Sq* daily variation rises from the early morning period to maximum at about local noon and falls to lower values towards evening; hence the ionospheric current responsible for the magnetic field variations was inferred to build up at the early morning periods and attain maximum intensity at about local noon. Rabiu *et al.* (2007b) analyzed magnetic records obtained at geomagnetic observatory of Addis Ababa in Africa during the sunspot minimum year 1986 for day-to-day variability of the hourly amplitudes of solar daily variation in H and Z geomagnetic field intensities. The variability was studied under quiet and disturbed conditions. Quiet day-to-day variability had consistent and explicable diurnal and seasonal variation and the daytime (0700-2000 hours) magnitudes were greater than the nighttime magnitudes (2000 -0700 hours through 2400 hours) for all the months in the two elements. Rabiu *et al.* (2011) examined the daily Sq for hourly profiles of H and D taken on 29th December, 2008 at ten MAGDAS stations along 96° Magnetic Meridian (MM) in Africa. The results showed that the H component experienced more variation within the equatorial electrojet zone. ElHawary *et al.* (2012) studied the daily Sq variations of the geomagnetic field by using the geomagnetic data of the ten International Quietest Days. Geomagnetic data from MAGDAS I and II stations were selected around the 96°MM over Africa and analyzed from September 2008 to August 2009. The work analyzed the H and D components of the geomagnetic field and found that *Sq(H)* and *Sq(D)* show a predominantly annual variation. Abbas *et al.* (2013) used hourly variation of two magnetic elements H and D from Aswan and Nairobi from January to December, 2008 to study the variation pattern of solar quiet and solar disturbed conditions. The variation pattern of *Sq* obtained showed that the maximum intensity occurred around local noon.

The main objective of the present study is to determine the mean annual variation of the quiet time geomagnetic field from the solar minimum year (2009) through solar maximum year (2014) to the start of the declining phase (year 2015) of Solar Cycle 24 with a view to investigating its solar activity

dependence and any unique features. Such a study has not been previously performed in the region of interest.

2. Data and Methods of Analysis

The present study uses the magnetic data from International Real-time Magnetic Observatory Network (INTERMAGNET) station at Addis Ababa (geomagnetic latitude 0.18°N, geomagnetic longitude110.47°E) and MAGnetic Data Acquisition System (MAGDAS) station at Nairobi (geomagnetic latitude 10.65°S, geomagnetic longitude 108.18°E).

The concept of local time was used throughout the analysis. The conversion from universal time (UT) to local time (LT) was done by considering that the Earth makes one complete rotation in 24 hours. It follows, therefore, that a longitudinal difference of 1° is equivalent to a time difference of 4 minutes. In this regard, the conversion from UT to LT was done according to:

$$LT = UT + \left(\frac{\alpha}{15}\right) \tag{2}$$

where α is the geodetic longitude of the station in question.

All the days with maximum $K_p \leq 2 +$ were classified as quiet days. Such days were extracted (from 1st January, 2009 to 31st December, 2015) from the list of K_p index posted by the World Data Centre for Geomagnetism, Kyoto on their website (http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/kp-cgi).

The present study analyzed the H-component of the geomagnetic field mainly because the region of study is equatorial where it is well known that the geomagnetic field is nearly horizontally directed North to South (Campbell, 1989) and the daily geomagnetic field variations, especially during quiet times, usually depend on the local tensor conductivity and the orientation of the main geomagnetic field.

A quiet level baseline was defined for each day as the arithmetic mean the geomagnetic field forthe first 300 minutes (5hours) starting from local midnight of the same day in a manner similar to that of (Yamazaki and Kosch, 2015).

In mathematical symbols, this means that;

$$H_0 = \sum_{t=1}^{300} \frac{H_t}{300} \tag{3}$$

The usage of these baselines is based on the assumption that the nighttime ionospheric currents are trivial. This assumption is generally accepted based on the fact that the conducting E region of the ionosphere largely disappears at night hours except at the auroral latitudes and currents flowing in the F region of the ionosphere during the night are much smaller in magnitude than the daytime dynamo currents (Takeda and Araki, 1985, Yamazaki *et al.*, 2011).

The baseline value for each day was subtracted from each of the one- minute resolution H-field values to get the variation amplitude from the baseline for the particular day. That is;

$$\Delta H_t = H_t - H_0 \qquad (4)$$

where t = 01 to1440, corresponding to the period00.00h to 23.98h. The resulting variation amplitude for any hour is associated with the ionospheric current at that hour (Rastogi *et al*., 2004).

During quiet times, the geomagnetic field variation is, theoretically, expected to exhibit a variation pattern similar to that of a periodic function diurnally in such, a way that the value at 00h should be equal to the value at 24h. However, this is not always necessarily the case in some data sets. A correction factor, known as non- cyclic variation, should therefore be performed on the data (Matsutisha and Maeda, 1965, Rastogi *et al*., 2004). The non-cyclic variation factor was defined as;

$$\Delta_c = \frac{(\Delta H)_1 - (\Delta H)_{1440}}{1439} \qquad (5)$$

where 1439 is the number of intervals in the data set.

Equation (5) can be expressed in the form:

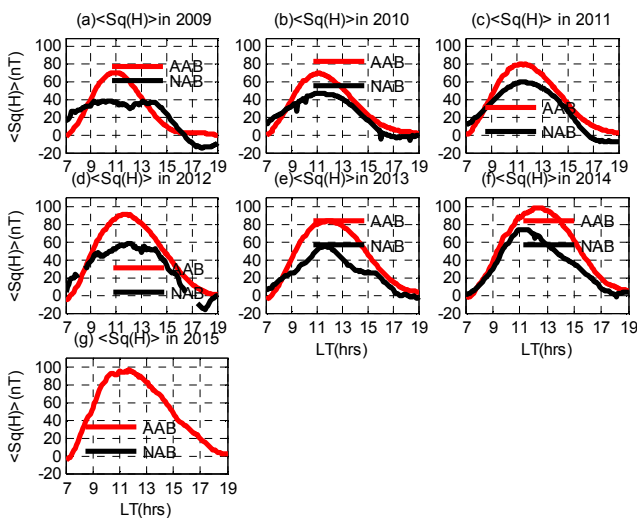$$(\Delta H)_1 = (\Delta H)_{1440} + 1439\Delta_c \qquad (6a)$$

Equation (6a) implies that in our new arrangement, the first data point will be given by the term on the right hand side, that is,

$$1^{st} = (\Delta H)_{1440} + 1439\Delta_c \qquad (6b)$$

We make a generalization by setting

$t = 1440 \Rightarrow 1439 = t - 1$ to write a general equation that represents the solar quiet daily variation as

$$Sq_t(H) = (\Delta H)_t + (t-1)\Delta_c : t = 1 : 1440 \qquad (7)$$

Figure 1. *Mean annual Sq (H) as a function of day light local time (LT) from 2009 to 2015.*

Equation (7) was used to determine the *Sq(H)* variation for each quiet day in the entire year. The average of these,

Sq(H) , variations for each year define the mean annual variation of the *H* field. The results are presented in Figure 1a, b, c, d, e, f and g.

3. Results and Discussion

Addis Ababa (AAB) is represented by the red colour while Nairobi (NAB) is represented by the black colour as illustrated by the legend. The margins have been removed from the legends. In the year 2015, Nairobi magnetometer recorded no data.

The amplitude of mean annual $Sq(H)$, ($< Sq(H) >$) shows a clear dependence on local time of the day at both stations: Addis Ababa and Nairobi.

At AAB, $< Sq(H) >$ increases from about 0 nT in the morning (around 0700 LT) attaining maximum values around 1100LT during low to moderate solar activity years (2009, 2010, 2011 and 2015) and 1200LT during high solar activity years (2012, 2013 and 2014), then decreases attaining values of about 0 nT in the evening at around 1700 LT. Nonetheless, at NAB, $< Sq(H) >$ generally increases from about 0 nT in the morning (around 0700 LT) attaining maximum values around 1130LT; then decreases attaining values around 0 nT in the evening at around 1700 LT. It is known that the maximum amplitude of *Sq(H)* appears before local noon in the range between 1030LT to 1130 LT during minimum sunspot years, around dip equatorial regions, and around local noon during maximum sunspot years (Rastogi and Iyer, 1976, El Hawary et al., 2012). One of the explanations suggested by Rastogi and Iyer, (1976) for maximum *Sq(H)* occurring well before noon is that, since *Sq(H)* represents currents in the ionosphere and current being a product of electron density, n_e, electronic charge, e, and charge drift speed, *v*, would be maximum at some point between the time of maximum electron density and drift speed. The electron density maximizes close to noon while the charge drift speed (hence the electric field) becomes maximum near 0900 to 1000 LT. It follows that the product (current) should maximize around 1100 LT. However, with increasing solar activity (sunspot number), the electron density is known to increase by 50% or more; whereas the electron drift speed remains constant or decreases. Thus the product of n_e and v should be able to shift to a later time near noon in high sunspot years.

Solar heating and ionization rates are important causes of *Sq(H)* at all latitudes. This accounts for the minimal values (around 0 nT) of $< Sq(H) >$ observed at AAB and NAB in the morning and evening hours, owing to low solar intensity at these hours.

The peak amplitude of $< Sq(H) >$ at AAB is consistently higher than the peak amplitude of $< Sq(H) >$ at NAB. This difference is attributed to the existence of the equatorial electrojet that intensifies just before local noon close to the geomagnetic equator (such as at AAB); hence imposing onto the *Sq(H)* current system. The equatorial electrojet is caused

by enhancement of the effective conductivity at the geomagnetic equator. For instance, consider a situation where the magnetic field is horizontal to the surface of the Earth as is the case at the geomagnetic equator. The direction of the magnetic field is from South to North, along the x-axis. The primary *Sq* Pedersen current flows eastward, in the y direction (orthogonal to the magnetic field), parallel to the primary ionospheric electric field. This primary electric field drives a Hall current which flows vertically downward in the z direction (perpendicular to both the primary electric field and the magnetic field), causing a charge separation in the equatorial ionosphere with negative charges accumulating at the top boundary and positive charges accumulating at the bottom of the highly conducting layer. This space charge distribution forms a secondary polarization electric field vertically directed from the bottom to the top of the conducting ionosphere. The polarization electric field drives a vertical Pedersen current opposing the Hall current until it fully cancels (compensates) it, resulting in an equilibrium condition in which no current flows in the vertical direction. Moreover, the secondary polarization electric field component generates a secondary Hall current component, flowing into the y direction.

The total current flowing in the eastward direction (positive y direction) is the sum of the primary Pedersen and the secondary Hall currents resulting in enhanced conductivity called Cowling conductivity. For typical Hall to Pedersen ratios lying in the range of 3 to 4, the Cowling conductivity is of order of magnitude higher than the usual Pedersen conductivity; hence explaining the amplification and concentration of the equatorial electrojet above the geomagnetic equator.

The amplitude of $< Sq(H) >$ at NAB is consistently higher than the amplitude of $< Sq(H) >$ at AAB in the morning hours between 0700-0800 LT. This difference is possibly due to the existence of a counter electrojet, a westward electric field close to the dip equator (such as at AAB) in the morning and/or evening hours; that tends to cancel (reduce) the $< Sq(H) >$ current system.

The maximum amplitude of $< Sq(H) >$ increases as solar activity increases. The largest increase occurs between solar minimum year (2009) and solar maximum year (2014), with about 50% and 75% for AAB and NAB respectively.

4. Conclusions

In the present study, the mean annual variation in *Sq(H)* at two stations (Addis Ababa and Nairobi) within the geomagnetic equatorial East African region has been investigated from the solar minimum year (2009), through the solar maximum year (2014) to the start of the declining phase (year 2015) of the Solar Cycle 24 with a view to determining its solar activity dependence and identifying any unique features in the variation. The amplitude of mean *Sq(H)* has shown dependence on local time of the day and solar activity. The mean *Sq(H)* increases steadily from

morning hours attaining peak values around 1100 LT at Addis Ababa during low to moderate solar activity years (2009, 2010, 2011 and 2015) and 1200 LT during high solar activity years (2012, 2013 and 2014), then decreases gradually attaining minimum values, around 0 *nT*, in the evening hours around 1700 LT. In Nairobi, the peak in mean *Sq(H)* is achieved around 1130 LT. This local time dependence is attributed to the variation in solar heating and ionization rates. Peak values of the mean *Sq(H)* are highest in solar maximum year. In addition, the morning mean *Sq(H)* at Nairobi is consistently higher than the corresponding values at Addis Ababa; attributed to the morning counter electrojet that acts to depress the *Sq(H)* current system closer to the geomagnetic equator.

Acknowledgements

References

[1]   Abbas, M., Zaharadeen, Y. J., Joshua, B. and Mohammed, S. (2013). Geomagnetic Field Variations at Low Latitudes along 96 degrees Magnetic Meridian. *International Journal of Marine, Atmospheric & Earth Sciences*, 1(2): 96-109.

[2]   Baumjohann, W. and Treumann, R. A. (1996). *Basic Space Plasma Physics.* London: Imperial College Press.

[3]   Campbell, W. (2003). *Introduction to geomagnetic fields* (2nd ed.). New York: Cambridge University Press.

[4]   Campbell, W. (1989). *Quiet Daily Geomagnetic Fields* (1st ed., Vol. 131). (W. H. Campbell, Ed.) Boston: Birkhiiuser Verlag Basel.

[5]   El Hawary et al. (2012). Annual and semi-annual Sq variations at 96° MM MAGDAS I and II stations in Africa. *Earth Planets Space*, 64, 425–432.

[6]   Matsushita, S., and Maeda, H. (1965). On the Geomagnetic Solar Quiet Daily Variation Field during the IGY. *Journal of Geophysical Research, 70* (11), 2535-2558.

[7]   Rabiu, A. (2001). Seasonal variability of Solar quiet at middle latitudes. *Ghana Journal of Science, 41*, 15-22.

[8]   Rabiu, A. B., Mamukuyomi, A. I. and Joshua, E. O. (2007). Variability of equatorial ionosphere inferred from geomagnetic field measurements. *Bull. Astr. Soc. India, 35*, 607-618.

[9] Rabiu, A. B., Nagarajan, N., Okeke, F. N., Ariyibi, E. A., Olayanju, G. M., Joshua, E. O. and Chukwuma, V. U. (2007). A Study Of day-to-day variability in geomagnetic field variations in the electrojet zone of Addis Ababa, East Africa. *African Journal of Science and Technology (AJST) Science and Engineering Series, 8* (2), 54-63.

[10] Rabiu, A. B., Yumoto, K., Falayi, E. O., Bello, O. R. & MAGDAS/CPMN Group. (2011). Ionosphere over Africa: Results from Geomagnetic Field Measurements During International Heliophysical Year IHY. *Sun and Geosphere, 6* (2), 63-66.

[11] Rastogi, R. G. and Iyer, K. N. (1976). Quiet Day Variation of Geomagnetic H-Field at Low latitudes. *J. Geomag. Geoelectr., 28*, 461-479.

[12] Rastogi, R. G., Kitamura, T. and Kitamura, K. (2004). Geomagnetic field variations at the equatorial electrojet station in Sri Lanka, Peredinia. *Annales Geophysicae, 22*, 2729-2739.

[13] Takeda, M. and Araki, T. (1985). Electric conductivity of the ionosphere and nocturnal currents. *Journal of Atmospheric and Terrestrial Physics, 47* (6), 601-609.

[14] World Data Center for Geomagnetism, Kyoto. (2016). *Geomagnetic Data Service.* Retrieved January 04, 2016, from http://wdc.kugi.Kyoto-u.ac.jp/cgi-bin/Kp-cgi

[15] Yamazaki, Y. and Kosch, M. J. (2015). The equatorial electrojet during geomagnetic storms and substorms. *Journal of Geophysical Research: Space Physics, 120*, 2276-2287, doi:10.1002/2014JA020773.

[16] Yamazaki, Y., Yumoto, K., Cardinal, M. G., Fraser, B. J., Hattori, P., Kakinami, Y., Liu, J. Y, Lynn, K. J. W., Marshall, R., McNamara, D., Nagatsuma, T., Nikiforov, V. M., Otadoy, R. E, Ruhimat, M., Shevtsov, B. M., Shiokawa, K., Abe, S., Uozumi, T. & Yoshikawa, A. (2011). An empirical model of the quiet daily geomagnetic field variation. *Journal of Geophysical Research, 116* (A10312), doi: 10.1029/2011JA016487.

Biography

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