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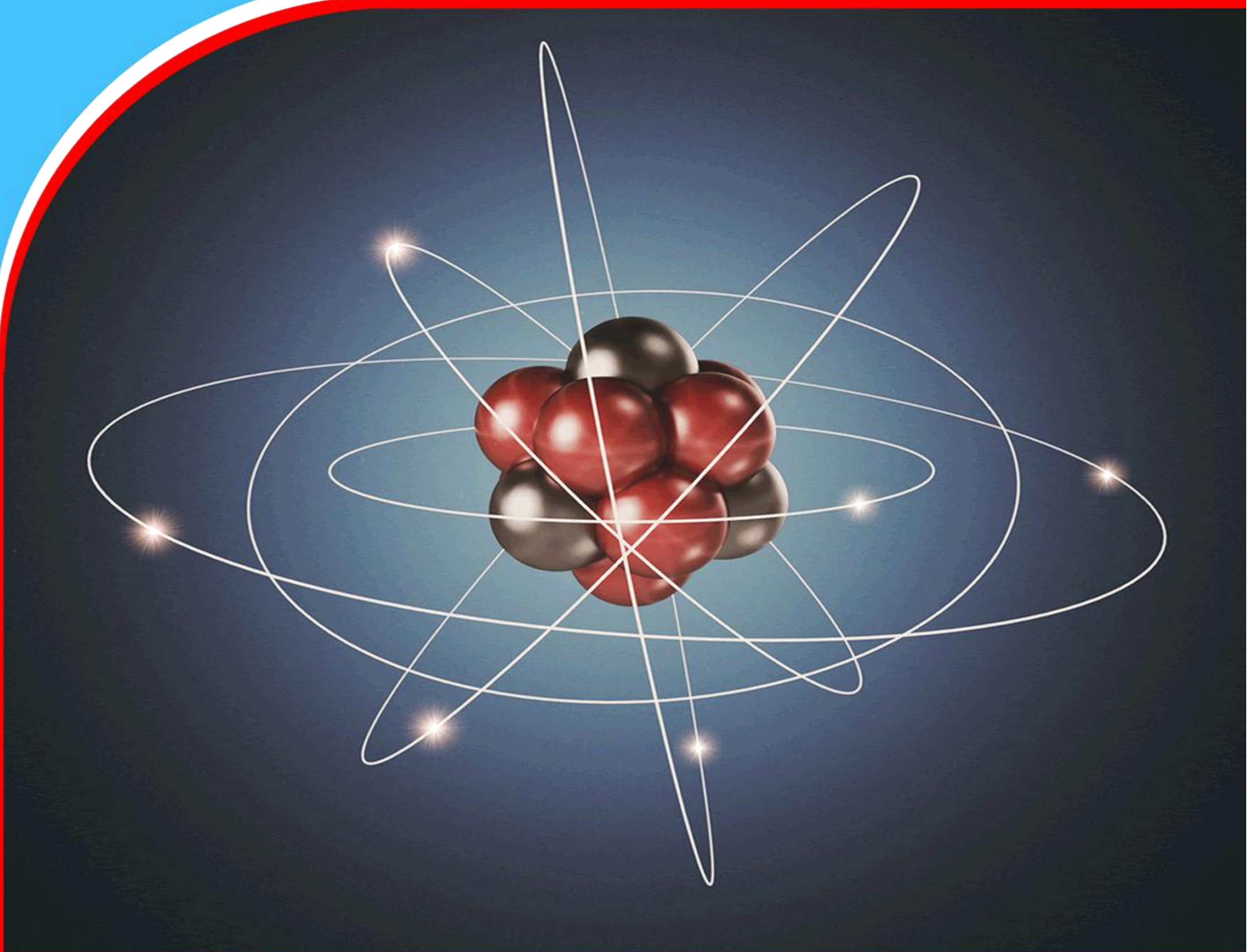

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ANALYSIS OF THE DAILY HOURLY DEPARTURES OF THE GEOMAGNETIC H FIELD OVER LOW-LATITUDE STATIONS

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Abstract

The telecommunication technologies deployed in the last decades have shown that there are better days ahead. From electric telegraphs systems in the 19th century to today's wireless communication using satellites and land links (Lanzerotti, 2001). The horizontal component (H-field) of the geomagnetic field has great impacts in the present-day communication technologies. The aim of this paper was to analyse the daily hourly departures of geomagnetic H-field along the low-latitude stations on the equatorial chain in relation to their correlation coefficients with their longitudes. The magnitude of H-component is a very significant factor in the determination of the total magnetic field of any location on the earth. The baseline values (H_0) which is the average of H components at 23LT, 24LT, 1LT and 2LT were subtracted from the hourly values of H (H_t) to obtain the hourly departures of H (dH). The hourly departures of H (dH) from the baseline is non-cyclic since $H_1 \neq H_{24}$ as observed over the three MAGDAS stations in Nigeria. The correlation coefficients between dHs of Lagos/Ilorin, Ilorin/Abuja and Abuja/Ilorin are 0.97, 0.75 and 0.66 respectively. This suggests that substorms are deflected eastwards along different longitudes due to the rotation of the earth such that locations in the same longitudes have the same hourly departures. There is no solar radiation during the nighttime, thus dH should be zero but for the energy stored in the magnetotail, the reduction of hourly departures towards nighttime in Nigeria is evident. This is further revealed as the midnight dH amplitudes decrease regularly. The eastward motion of the electrons during substorms was suggested to be responsible for the reduction of the H-field at the nightside magnetotail region for all the stations. These findings will assist the telecommunication companies to know which location is best for their transmitters to be sited in order to reduce loss of signals along the optical cables to the receivers. Furthermore, global telecomms companies should have business continuity plan which should include risk assessment and prompt response to geomagnetic disturbances being one of the causes for telecommunication outages.

Keywords: *Hourly departures,non-cyclic, correlation coefficient, magnetotail*

1. INTRODUCTION

Lanzerotti (2001) reiterated that in the last century and one-half, the variety of communications technologies that are embedded in space-affected environments have vastly increased. He presented a paper on space weather as it affects communications, beginning with the earliest electric telegraph systems and continuing to today's wireless communications using satellites and land links. He added that solar- terrestrial phenomena such as galactic cosmic rays, solar-produced plasmas, and geomagnetic disturbances in the Earth's magnetosphere can affect the present-day communications technologies. Globalized corporations depend upon information and communication technologies as a component of their strategic plans; hence, deciphering and mitigating risk to these technologies is vital to corporate business continuity plans (McManus *et al.*, 2011).

Spherical harmonic analysis is a powerful technique to describe the global distribution of the geomagnetic field including, but not limited to, the solar quiet *(Sq)* field. The *Sq* field at a certain location can be measured using a magnetometer. However, ground-based measurements can cover only a limited area of the surface due to, for example, the presence of oceans. Thus, at the locations where there are no measurements, the *Sq* field needs to be estimated by an interpolation of existing data. (Yamazaki *et al.*, 2017). Many authors have studied long-term changes in *Sq* variations. Takeda, (1999, 2002) stated that the midlatitude *Sq* current intensity during solar maximum is approximately twice as high as that during solar minimum. Yamazaki and Yumoto, 2012, Çelik, *et al.*, 2012 stipulated that solar activities modulate the amplitude and phase of seasonal *Sq* variations. It has been established that solar activity dependence of *Sq* variations is mainly due to enhanced ionospheric conductivities during high solar activity periods, which lead to increased ionospheric currents (Takeda *et al.*, 2003). Also, the high-latitude electric field, driven by the magnetospheric dynamo, is enhanced during high solar activity periods, which leaks to lower latitudes and affects *Sq* currents (Zaka *et al.*, 2010).

A geomagnetic storm can be characterized by rapid fluctuations of geomagnetic field which can induce GIC (Geomagnetically Induced Currents) in technological systems, affect radio waves travelling through the ionosphere (scintillation) as well as produce beautiful auroras in mid-latitudes (Honore *et al.*, 2014). The equatorial electrojet current (EEJ) produces a strong enhancement in the H component magnetic field measured by magnetometers located within ±3 of the magnetic equator. Obiekezie *et al.*,(2013) found that, for the EEJ stations, when the widths of both the electrojet and the counter-electrojet are nearly equivalent, the amplitude of variation is greatly reduced. James *et al.*, (2008) explained that during the geomagnetic disturbed days, the protons drift closer to the earth than the electrons,even though they have the same energy in the tail. Hence, the currents produced by the protons, which drift towards dusk are stronger than those produced by the electrons (Kavanagh *et al.*,1968), causing a larger decrease of H field in the late evening hours. In view if this, there should be a close correlation between the day-to-day variations in the daily range of H-field and the Disturbed Storm Time (Dst) index in a given region of almost same longitude and different latitudes (Kane, 1971).

The magnetosphere in its quiet state behaves like a dipole. But during storms, the effect of the solar wind stresses the anti-sunward region of the magnetosphere into a long magnetic tail which make the normal H-field to differ as the storm persists. This paper investigated the nature of hourly departures (dH) at the three low-latitude stations in Nigeria located at Lagos (6.48^o*N*, 3.27^o*E*), Ilorin (8.50^{o}N, 4.68^o*E*) and Abuja (8.99^o*N*, 7.39^o*E*) and to deduce the mechanism responsible for the observed variations.

2. METHOD OF ANALYSIS

The primary data used in this study was the horizontal component (H) of the geomagnetic field obtained from Magnetic Data Acquisition System (MAGDAS) ground based observatories at the three Nigerian stations located at Lagos, Ilorin and Abuja. Table 1 below shows the details of these locations.

Table 1: List of stations with their coordinates

Stations	Geographic Latitude (°N)	Geographical Longitude (°E)	Geomagnetic Latitude (°N)	Geogmagnetic Longitude (°E)	L (°)	Dip Latitude (°)
Lagos	6.48	3.27	-3.04	75.33	1.00	-4.95
Ilorin	8.50	4.68	-1.82	76.80	1.00	-2.96
Abuja	8.99	7.39	-0.54	81.31	1.00	-0.95

The local time (LT) for the three stations was used for this study. The baseline values (H_0) in equation (1) were calculated as the average of the values of the flanking one hour before midnight, midnight and two hours after midnight.

Mathematically,

$$H_0 = \frac{H_{23} + H_{24} + H_1 + H_2}{4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

Where H_1, H_2, H_{23} and H_{24} are the hourly values of H at 1, 2, 23 and 24 LT hours respectively.

The hourly departures of H from the baselines values dH were acquired by subtracting the baseline values for a particular day H_0 from the hourly values for that particular day H_t.

Therefore, for the hour t,

$$dH_t = H_t - H_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

Where t = 1, 2, 3…, 24 LT.

The activities of the magnetosphere on a quiet day speak more of its natural behavior. The International Quiet Days (IQD) data for the year 2010 was selected for this study. The year 2010 is a year with ascending solar spot numbers (SSN) as shown in Figure 1 below. One of the IQDs, 11 December 2010 was selected for the three stations in order to observe the day-to-day variation of H –field across the stations.

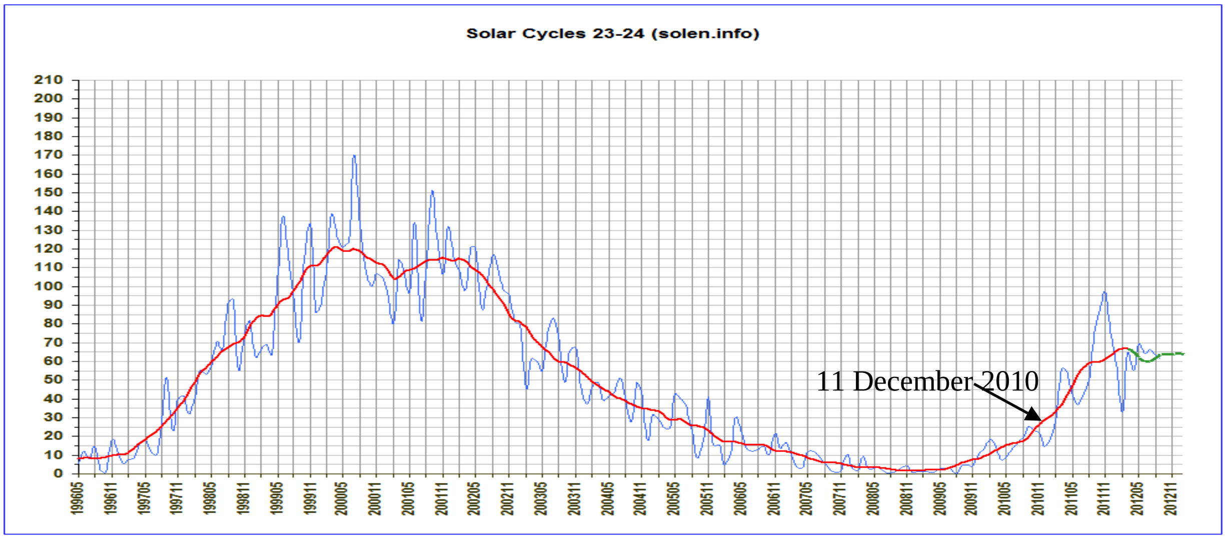

Figure 1: Solar cycle 24 showing the day of study

Using equation (2) above, the dHs for each station were derived and analyzed. Their maximums and minimums were also verified and the correlation coefficient table was designed to verify that within the equatorial zone, the geomagnetic field intensities on quiet time vary from one longitudinal sector to another as observed by Doumouya *et al.*, (2003).

3. RESULTS/DISCUSSION

The results retrieved from equations 1 and 2 are charted in Tables 2, 3 and 4 below.

For Lagos Station (LAG), we have

$$H_0 = \frac{32048.61 + 32049.75 + 32038.53 + 32041.03}{4} = 32044.48nT$$

$$dH_1 = 32038.53 - 32044.48 = -5.95nT$$

Subsequently, the values of dH_t were obtained.

Table 2: The values of H_t and dH_t for Lagos Station on 11 December 2010

LT (Hrs)	H_t (nT)	H_o (nT)	dH_t (nT)
1	32038.53	32044.48	-5.95
2	32041.03	32044.48	-3.45
3	32040.65	32044.48	-3.83
4	32041.97	32044.48	-2.51
5	32043.97	32044.48	-0.51
6	32040.72	32044.48	-3.76
7	32039.72	32044.48	-4.76
8	32045.03	32044.48	0.55
9	32061.02	32044.48	16.54
10	32074.89	32044.48	30.41
11	32087.51	32044.48	43.03
12	32086.23	32044.48	41.75
13	32072.82	32044.48	28.34
14	32063.85	32044.48	19.37
15	32065.22	32044.48	20.74
16	32061.03	32044.48	16.55
17	32055.12	32044.48	10.64
18	32053.16	32044.48	8.68
19	32050.37	32044.48	5.89
20	32047.58	32044.48	3.10
21	32045.22	32044.48	0.74
22	32045.14	32044.48	0.66
23	32048.61	32044.48	4.13
24	32049.75	32044.48	5.27

From the Table 2 above, the maximum and minimum values of dH are 43.03nT and -5.95nT respectively. Hence, the range is 48.98nT. Since $H_1 \neq H_{24}$, then the variation is non-cyclic. The mean value of dH is 9.65nT.

For Ilorin Station (ILR), we have

$$H_0 = \frac{32828.54 + 32827.35 + 32817.81 + 32820.56}{4} = 32823.57nT$$

$$dH_1 = 32817.81 - 32823.57 = -5.76nT$$

Subsequently, the values of dH_t were obtained.

Table 3: The values of H_t and dH_t for Ilorin Station on 11 December 2010

LT (Hrs)	H_t (nT)	H_o (nT)	dH_t(nT)
1	32817.81	32823.57	-5.76
2	32820.56	32823.57	-3.01
3	32820.36	32823.57	-3.21
4	32821.81	32823.57	-1.76
5	32823.47	32823.57	-0.10
6	32819.83	32823.57	-3.74
7	32819.63	32823.57	-3.94
8	32830.64	32823.57	7.07
9	32857.41	32823.57	33.85
10	32874.73	32823.57	51.17
11	32884.43	32823.57	60.86
12	32880.95	32823.57	57.38
13	32864.24	32823.57	40.67
14	32846.96	32823.57	23.39
15	32843.91	32823.57	20.35
16	32838.56	32823.57	14.99
17	32833.62	32823.57	10.06
18	32828.11	32823.57	4.54
19	32826.66	32823.57	3.10
20	32824.91	32823.57	1.35
21	32822.99	32823.57	-0.58
22	32822.91	32823.57	-0.65
23	32827.35	32823.57	3.78
24	32828.54	32823.57	4.97

From the Table 3 above, the maximum and minimum values of dH are 60.86nT and -5.76nT respectively. Hence, the range is 66.62nT. Since $H_1 \neq H_{24}$, then the variation is non-cyclic. The mean value of dH is 13.12nT.

For Abuja Station (ABU), we have

$$H_0 = \frac{32799.06 + 32786.77 + 32803.93 + 32804.23}{4} = 32798.50nT$$

$$dH_1 = 32803.93 - 32798.50 = 5.43nT$$

Subsequently, the values of dH_t were obtained.

Table 4: The values of H_t and dH_t for Abuja Station on 11 December 2010

LT (Hrs)	H_t (nT)	H_o (nT)	dH_t (nT)
1	32803.93	32798.50	5.43
2	32804.23	32798.50	5.73
3	32805.28	32798.50	6.78
4	32804.08	32798.50	5.58
5	32805.97	32798.50	7.47
6	32809.10	32798.50	10.60
7	32813.61	32798.50	15.11
8	32822.57	32798.50	24.07
9	32836.63	32798.50	38.13
10	32862.24	32798.50	63.74
11	32854.19	32798.50	55.69
12	32821.45	32798.50	22.95
13	32811.48	32798.50	12.98
14	32812.72	32798.50	14.22
15	32834.43	32798.50	35.93
16	32818.40	32798.50	19.90
17	32806.23	32798.50	7.73
18	32789.49	32798.50	-9.01
19	32799.89	32798.50	1.39
20	32799.05	32798.50	0.55
21	32806.87	32798.50	8.37
22	32802.24	32798.50	3.74
23	32799.06	32798.50	0.56
24	32786.77	32798.50	-11.73

From the Table 4 above, the maximum and minimum values of dH are 63.74nT and -11.73nT respectively. Hence, the range is 75.47nT. Since $H_1 \neq H_{24}$, then the variation is non-cyclic. The mean value of dH is 12.39nT

The values of dH_{max}, dH_{min}, dH_{midday}, and $dH_{midnight}$ for each station on 11 December 2010 are summarized in Table 5 below.

Table 5: The magnetic parameters of the three stations.

Stations	**Latitude (°N)**	**Longitude (°E)**	**dH_{max} (nT)**	**dH_{min} (nT)**	**dH_{midday} (nT)**	**$dH_{midnight}$ (nT)**
LAG	6.48	3.27	43.03	-5.95	41.75	5.27
ILR	8.50	4.68	60.86	-5.76	57.38	4.97
ABU	8.99	7.39	63.74	-11.73	22.95	-11.73

The maximum dH increases as the latitude increases and at midnight, the amplitude of dH reduces as the latitude increases as shown in Table 5 above. Plasma flow on the equatorward edge of sub-auroral polarization stream is always westwards and becomes more westward as the latitude increases (Anderson *et al.*, 1991).

Table 6: The values of dH for Lagos, Ilorin and Abuja and their hourly means

LT	Lagos dH(nT)	Ilorin dH(nT)	Abuja dH(nT)	Hourly Mean dH(nT)
1	-5.95	-5.76	5.43	-2.09
2	-3.45	-3.01	5.73	-0.24
3	-3.83	-3.21	6.78	-0.08
4	-2.51	-1.76	5.58	0.44
5	-0.51	-0.10	7.47	2.29
6	-3.76	-3.74	10.60	1.04
7	-4.76	-3.94	15.11	2.14
8	0.55	7.07	24.07	10.57
9	16.54	33.85	38.13	29.51
10	30.41	51.17	63.74	48.44
11	43.03	60.86	55.69	53.20
12	41.75	57.38	22.95	40.70
13	28.34	40.67	12.98	27.33
14	19.37	23.39	14.22	19.00
15	20.74	20.35	35.93	25.67
16	16.55	14.99	19.90	17.15
17	10.64	10.06	7.73	9.48
18	8.68	4.54	-9.01	1.41
19	5.89	3.10	1.39	3.46
20	3.10	1.35	0.55	1.67
21	0.74	-0.58	8.37	2.85
22	0.66	-0.65	3.74	1.25
23	4.13	3.78	0.56	2.83
24	5.27	4.97	-11.73	-0.49
Max	43.03	60.86	63.74	53.02
Min	-5.95	-5.76	-11.73	-0.08
Correlation coefficient for LAG/ILR				0.971941
Correlation coefficient for ILR/ABU				0.758356
Correlation coefficient for ABU/LAG				0.668173

With a correlation coefficient of 0.97, it suggests that there are simultaneous increments in the dH in Lagos and Ilorin. As stipulated in Table 6 above, it clearly shows that an increase in the dH in Lagos implies an increase of dH in Ilorin and Abuja subsequently. This can only occur if the source of the dH is from one point. Despite the latitudinal and longitudinal differences, the three stations share the same source of substorm. Moreover, Table 5 showed that the maximum dH for each station increases as their latitudes increases while the minimum dH is irregularly decreasing as their latitudes increases.

Table 7: The correlation coefficient between dHs of pairs of the stations

Stations	R	difference in Latitude (°N)	difference in Longitude (°E)
LAG/ILR	0.97	2.02	1.41
ILR/ABU	0.76	0.49	2.71
ABU/LAG	0.67	2.51	4.12

The analysis of the Table 7 above shows that the dH in Lagos and Ilorin are well correlated with a value of 0.97. This suggests that the daily hourly departures have definite pattern such that an increase in amplitude in Lagos will reciprocate in Ilorin. Moreso, that the difference in their longitudes is small compared to Ilorin/Abuja and Abuja/Lagos. Doumouya *et al.,* (2003) suggested that locations within same longitudes would have same hourly departure from baseline. Locations with larger longitudinal differences were less correlated.

The amplitudes of dH for the three stations were plotted against time on 11 December 2010 as shown in Figure 2 below.

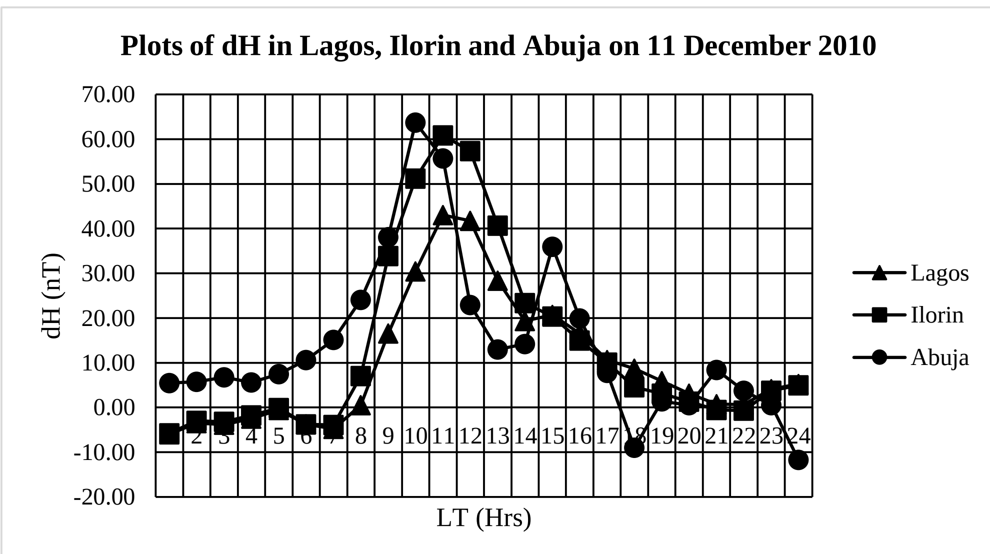

Figure 2: The plot of dH in Lagos, Ilorin and Abuja on 11 December 2010

The results from the plots in Figure 2 reveal the followings on a typical quiet day in Nigeria:

(a) **Peaks:** There are two peaks occurring around 10LT – 11LT during the main phase of the geostorm and around 15LT during the recovery phase. This is because the free electrons formed during the intense solar radiation excites the stored charged particles in the magnetotail which were inactive over the night. So, before noon, peaks are attained. Furthermore, shortly after the "before noon" peaks, the intensity of the solar radiation is increased and more electrons are freed into the outer space which depicts the second peaks.

(b) **Amplitude of dH:** The amplitudes of dH in Lagos and Ilorin are relatively very close till 7LT than that of Abuja which is higher than both Lagos and Ilorin. At 8LT, the amplitudes of Ilorin disperse higher than that of Lagos until 15LT where it becomes low till 23LT where it becomes close again. This equatorial enhancement is as a result of equatorial electrojet current derived from the solar radiation.

(c) **Time Shift:** There is a time shift in the geomagnetic variation of H (dH) such that its peak occurs at 10LT in Abuja and at 11LT simultaneously in Ilorin and Lagos. This confirms that the trickling effect of the poloidal substorms occurs early in higher latitudes.

Table 8: The values of dH in the three station during nighttime and daytime

LT	Lagos	Ilorin	Abuja
1	-5.95	-5.76	5.43
2	-3.45	-3.01	5.73
3	-3.83	-3.21	6.78
4	-2.51	-1.76	5.58
5	-0.51	-0.10	7.47
6*	-3.76	-3.74	10.60
7*	-4.76	-3.94	15.11
8*	0.55	7.07	24.07
9*	16.54	33.85	38.13
10*	30.41	51.17	63.74
11*	43.03	60.86	55.69
12*	41.75	57.38	22.95
13*	28.34	40.67	12.98
14*	19.37	23.39	14.22
15*	20.74	20.35	35.93
16*	16.55	14.99	19.90
17*	10.64	10.06	7.73
18*	8.68	4.54	-9.01
19	5.89	3.10	1.39
20	3.10	1.35	0.55
21	0.74	-0.58	8.37
22	0.66	-0.65	3.74
23	4.13	3.78	0.56
24	5.27	4.97	-11.73

Note that the * indicates the LT during the day

It has been shown from the Table 8 above that amplitudes of dH are higher during the daytime (6LT - 18LT) and lower during the nighttime (19LT - 5LT). Sarabhai & Nair (1971) have proposed that factors such as (i) the atmospheric dynamo current at ionospheric E-region; (ii) the surface current at the magnetopause and (iii) the tail current, the symmetrical equatorial ring current, eccentric ring current and the partial ring current in the magnetosphere might be the reason for daily variation of the horizontal component of H field at low latitude stations. Mead, (1964) agreed that during the nighttime at the surface of the earth, the magnetopause currents due to the corpuscular flux have been shown to be same.

The tangential stress at the magnetopause increases the magnetic energy stored in the tail, which results in the increase of tail radius and the movement of inner edge of the neutral sheet close to the earth (Siscoe & Cummings, 1969). Axford, Petschek & Siccoe (1965) and Williams & Mead (1965) have revealed in their literature work that the effect of neutral sheet and the current system in the tail results in the decrease of the H-field during nighttime at low latitude. This sheet shares similarity with amagnetic dipole of opposite magnetic moment to that of the main geomagnetic field. The symmetric ring current events on quiet dayscontribute to a decrease of about 28 nT in H-field at the surface of earth (Schield 1969a, b). The contours of B in the equatorial plane are nearer to the earth in the anti-solar direction compared to the sub-solar direction (Fairfield 1968). This eccentricity of the B contours is enhanced when the solar wind pressure is more. Therefore, the decrease of H field due to the eccentric ring current is more during the nighttime than during the daytime. During the geomagnetic disturbed days, the protons drift closer to the earth than the electrons, even though they have the same energy in the tail (Freeman & Magure 1967, Cummings, Barfield & Coleman 1968). Therefore, the currents produced by the protons, which drift towards dusk are stronger than those produced by the electrons (Kavanagh *et al.*, 1968), causing a larger decrease of H field in the late evening hours as shown in Table 8.

CONCLUSION

The investigation of the dH in Nigeria using the geomagnetic field measurement of the three stations located in Lagos, Ilorin and Abuja shows that the amplitudes of dH are higher during the daytime (6LT-18LT) and lower during the nighttime (19LT-5LT). Moreso, the dHs are latitudinal dependent. The higher the latitude, the higher the dH. This suggests that the source of these fluctuations is the result of some distant magnetospheric processes. The dHs are also longitudinally correlated. The higher the difference in longitude, the less correlated the dH of the stations as seen in Table 2. This is a confirmation that the occurrence of Pi2 tilts eastward towards nighttime as observed by Chapman (1951) and Doumouya *et al.*, (2003). All the peak dHs occur in the daytime. During the main phase of the storm, the first dH peak in Abuja occurred at 10LT while in Ilorin and Lagos, it was at 11LT simultaneously. But, during the recovery phase, the dH peaks for the three stations occurred at 15LT. At midday, the amplitudes of the dHs of the three stations were irregular while at midnight, they were decreasingly regular. However, the maximum values of dHs increase with latitudes while the minimum values are irregular with increase in latitudes.

RECOMMENDATION

It is imperative to know that modern technologies are adversely affected by solar storms, hence, organizations must recognize the need for a business continuity plan that can address wired and wireless environments. As the earth rotates, global branches of large organizations that have worldwide locations have increased vulnerability to solar activities due to the networking of the branches.

Telecommunication systems of corporations are at risk of security breach when there is geomagnetic disturbances. Information and communication technologies are components used for strategic planning in globalized corporations, thus, tracing and trying to lessen the risk to these technologies is very key to corporate business continuity plans. A huge dH in a location can affect hundreds of millions of mobile device carriers who might be on calls, or financial transactions, or teleconferencing or any other digital engagement at the time of storm which will lead to heavy revenue loss and other forms of damages. It is further recommended that companies with the intention of global locations should consider the impact of geomagnetic disturbances during a particular season and time of the day in the proposed locations. Business continuity strategies should be in place to help respond promptly to geomagnetic disturbances which is one of the causes of information technology outages.

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