Understanding the global dynamics of the equatorial ionosphere in Africa for space weather capabilities: A science case for AfrequaMARN

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Abstract

The equatorial region of the Earth's ionosphere is one of the most complex ionospheric regions due to its interactions, instabilities, and several unresolved questions regarding its dynamics, electrodynamics, and physical processes. The equatorial ionosphere overall spans three continents with the longest region being that over the African continent. Satellite observations have demonstrated that very large differences exist in the formation of ionospheric irregularities over the African sector compared with other longitudinal sectors. This may be a consequence of the symmetric shape of the magnetic equator over the continent and the lack of variability in latitude. In this paper, we propose a science campaign to equip the African sector of the magnetic equator with ground-based instruments, specifically magnetometers and radars. The network of radars proposed is similar in style and technique to the high-latitude SuperDARN radar network, while the magnetometers will form an array along the equatorial belt. These two proposed space physics instruments will be used to study this region of the equatorial ionosphere over a long interval of time, at least one solar cycle. The deployment of an array of magnetometers (AfrequaMA) and a radar network (AfrequaRN) in the African sector of the magnetic equator is jointly called the Africa Equatorial Magnetometer Array and Radar Network (AfrequaMARN), which will provide simultaneous observations of both electric and magnetic variations over the African sector. We also examine the possible science questions such a magnetometer array and radar network would be able to address, both individually and in conjunction with other space-based and ground-based instrumentation. The proposed projects will clearly improve our understanding of the dynamics of the equatorial ionosphere and our understanding of its role in balancing the large-scale ionospheric current system, and will contribute to our ability to adequately model ionospheric and plasmaspheric densities. It will also enhance our understanding of global ionospheric processes, which will improve the space weather capabilities of the African and international space science communities.

Keywords: Equatorial ionosphere, AfrequaMARN, SuperDARN, instrumentation

1. Introduction

The terrestrial ionosphere is the uppermost part of the Earth's atmosphere where charged plasma particles with a typical energy lower than 1 eV are created, which affects the propagation of radio waves by changing their speed and direction (Wernik et al., 2003). It can be classified into polar, high latitude (auroral), mid latitude, and equatorial or low latitude regions. The conditions on the Sun, the solar wind, the magnetosphere, ionosphere and thermosphere that can affect the performance and reliability of space-borne and ground-based technological systems and that can also endanger human life is known as space weather. Schrijver et al. (2015) noted that space weather can be categorised into mild or extreme events. The impacts of mild space weather events can cause ionospheric disturbances and irregularities which can cause degradation of electric power quality, fluctuations of radio signals (scintillations), radar range errors, perturbation of the precision of navigation systems, interruption of satellite functions, and hazards to astronaut health while impacts of extreme events include loss of satellites and interruptions of the electric power system (Seo et al., 2011, Schrijver et al., 2015). Figure 1 shows variations in the occurrence of radio scintillations with geographic location, taken from Kintner et al. (2009). It shows where scintillation will most frequently affect radio signals during solar maximum.

The Earth's equator is uniquely the region where the magnetic field lines lie approximately horizontal within the ionosphere. The morphology is thus entirely distinct from that at higher latitudes where the field threads more nearly vertically through the ionospheric layer (Basu et al. 2002; de la Beaujardière et al., 2004). It is the most complex region of the Earth's ionosphere and is also host to the most complex phenomena in the upper atmosphere.

Figure 1. Map showing the frequency of scintillation disturbances at solar maximum with peaks in two bands surrounding the magnetic equator. (Adapted from Kintner et al. (2009)).

It is susceptible to electrodynamic interactions, plasma processes, and ionospheric instabilities which are fundamental physics processes. The complexity is due to the north-south direction of the Earth's magnetic field combined with the vertical direction of the electron density gradient, with transport-related field-perpendicular electric fields directed both east-west and vertical. The equatorial region may also be disturbed by coupling to the high latitude ionosphere which is in turn disturbed by solar wind and magnetospheric processes. Such processes include the high speed streams of coronal mass ejections which cause rapid changes in solar wind dynamic pressure, solar flares, together with geomagnetic storms and substorms.

The Earth's magnetic equator passes through three continents, i.e., the African, American, and Asian sectors, with the African continent having the longest land-based magnetic equatorial segment out of these three (see Figure 1). Considerable progress has been made in our efforts to understand the electrodynamics, the plasma processes, the ionospheric irregularities, and the coupling phenomena in the American and Asian longitudinal sectors in the last six decades, due to the availability and use of large distributions of ground-based and satellite based instrumentation (Lester, 2008). In particular, major contributions to understanding the structure of the equatorial

ionosphere has been made by observations at the Jicamarca Radio Observatory in Peru (Kelley, 1989; Schunk & Nagy, 2009). However, recent satellite observations have shown that the structure of ionospheric irregularities over the African sector is distinct from the ionospheric structures in the other equatorial ionospheric sectors, hence the region responds to space weather differently to other sectors (Burke et al., 2004; de la Beaujardière et al., 2004; Amory-Mazaudier et al., 2005; Hei et al., 2005; Burke et al., 2006; Kintner et al., 2009; Yizengaw et al., 2013). Equatorial plasma bubbles can affect radio communications, interruptions to satellites communications, and disruptions to Global Navigation Satellite Systems (GNSS) signals, which could have important consequences for communication and navigation. Figure 2 shows equatorial plasma bubbles (EPBs) observed over Africa by the Global Ultraviolet Imager (GUVI) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite using airglow emissions (Yizengaw et al., 2013).

Figure 2. Equatorial plasma bubbles over Africa as seen in airglow depletions observed by the Global Ultraviolet Imager (GUVI) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. The dark patches within the brighter equatorial “arcs,” either side of the geomagnetic equator (dotted line), are where communication signals would be lost (Adapted from Yizengaw et al. (2013)).

The dark patches within the brighter equatorial “arcs” on either side of the African sector of the geomagnetic equator, the dotted line in Figure 2, are the regions where satellite signals would be scintillated, and where communications signals would be lost. Gentile et al. (2006) used additional data to extend the studies of Burke et al. (2004a,b) on the global climatology of equatorial plasma bubbles (EPBs), based on plasma density measurements by the polar-orbiting Defense Meteorological Satellite Program (DMSP) spacecraft during 1989–2004. The interval of their study encompasses two solar maxima and a solar minimum, which provides the opportunity to investigate the global distribution of EPBs on different time scales and solar cycle phases. Contrary to expectations, the Atlantic-African sector shows an enhanced occurrence rate of EPBs compared to other sectors of the dip equator. Likewise, as shown in Figure 3, Gentile et al. (2011) carried out a study which also showed that the plasma bubbles observed in the African sector are stronger than those observed in other equatorial longitudinal sectors.

Figure 3. Contour plot of evening sector EPB rates observed by DMSP F15 during solar maximum year 2000 by month and longitude showing maximum occurrence rates (>70%) over the Atlantic-Africa sector. (Adapted from Gentile et al. (2011)).

The differences in the ionospheric irregularities observed in the African sector and other equatorial sectors could be due to differences in the symmetry of the African sector in comparison to the American sector (Figure 1). In addition, the spatial extent of the equatorial ionosphere over the African continent could also be a possible factor. Previous observations in this sector were

conducted during the interval September 1991 to March 1993, designated as the International Equatorial Electrojet Year (IEEY) at the sixth scientific assembly of the International Association of Geomagnetism and Aeronomy (IAGA) held in Exeter, United Kingdom, in 1989. IEEY was an intensive and coordinated programme on the equatorial electrojet (EEJ) and related phenomena organized by IAGA's Inter-Divisional Commission on Developing Countries, which was designed to improve the understanding of the geophysical, aeronomic, electrodynamic, and plasma processes that control the EEJ current, its spatial structure, space and time variations, instabilities, and induced effects (Abdu, 1992). Observational campaigns were planned to investigate longitude effects, the longitude-latitude variations in EEJ behaviour, the counter electrojet phenomenon, and EEJ coupling with high latitude processes especially in association with magnetic storms and other solar wind-related disturbances (Abdu, 1992). During the IEEY, several instruments were deployed at Korhogo (Côte D'Ivoire), including an HF radar during two campaigns (April–July 1993 and October–December 1994), an optical (630 nm) Fabry-Perot interferometer, an ionosonde, and a magneto-telluric magnetometer (November 1992 to October 1994), which were used to study the equatorial ionosphere over Africa (Amory-Mazaudier et al., 2005). Most of the campaigns in this sector, however, were short lived, for a few days or months, either due to the objectives of the campaign or due to operational difficulties.

Figure 4. Coverage of ground-based instrumentation in Africa (a) in 2007, and (b) in 2012. (Adapted from Yizengaw et al. (2013).)

The electrodynamics, the plasma processes, and the coupling processes in the African sector of the equatorial region have not received the required attention of researchers using ground-based instruments by comparison with other equatorial sectors. Figure 4a shows the coverage of ground-based instruments in Africa in 2007, while Figure 4b shows the distribution of ground-based instruments in 2012. The distribution of ground-based instruments includes the Magnetic Data Acquisition System/Circum-Pan Pacific Magnetometer Network (MAGDAS/CPMN) which is an array of magnetometers deployed for the study of the dynamics of geospace plasma changes during magnetic storms and auroral substorms covering the polar, mid-latitude, and equatorial regions, installed by the Space Environment Research Center (SERC), Kyushu University, Fukuoka, Japan ("MAGDAS|ISWI Secretariat"). It also includes the Scintillation Network Decision Aid (SCINDA) system which provides real time communication outage forecasts and alerts to aid the prediction of satellite signal degradation in the equatorial region developed for the United States Air Force Space Command by the Air Force Research Laboratory (AFRL) ("SCINDA | ISWI Secretariat"), and the African Meridian B-Field Education and Research (AMBER) array, a NASA-IHY funded array of four magnetometers in Algeria, Ethiopia, Namibia, and Cameroon ("AMBER | ISWI Secretariat").

Although instrumentation has increased in recent years, the distribution of ground-based instruments remains uneven, and hence there remain a number of unanswered questions concerning the nature of the electrodynamics governing some parts of the ionosphere. This serves as one reason for our lack of detailed understanding and explanation of the physics behind some events in solar-terrestrial relations. Here we thus propose two projects to be deployed near-simultaneously for the study of the African equatorial sector. The first phase proposes the use of a network of radars, which we refer to as the Africa Equatorial Radar Network (AfrequaRN). This is a subset of a proposed global project called the Equatorial (Dual) Electrojet Radar Network (EquaERN (EquaDERN)) and Equatorial Magnetometer arrays. The second phase proposes an array of magnetometers referred to as the Africa Equatorial Magnetometers (AfreqMAG). This two-in-one project is what we jointly refer to as the Africa Equatorial Magnetometer Array and Radar Network (AfrequaMARN).

2. African Equatorial Ionosphere

The African continent (Figure 5) is the second largest out of all the continents, being three times the size of the United States of America. It contains the largest tropical land mass and the largest desert in the world. It is bounded in the east by the Indian Ocean, in the west by the Atlantic Ocean, and in the north by the Mediterranean Sea. Both the magnetic equator (red line in Figure 5) and the geodetic equator pass through the African continent and are well aligned together.

Figure 5. Map of Africa showing the magnetic equator in red. (Map courtesy of the Nations Online Project).

The equatorial ionosphere over Africa is spatially the longest sector out of the three sectors of the equatorial ionosphere and is also symmetric in comparison with the American sector shown in Figure 1. The continent has the largest landmass underneath the Earth's magnetic equator in the world making it a very good environment for the study of equatorial ionospheric dynamics and plasma processes. Table 1.1 gives a list of African countries within the magnetic equatorial region, together with the geographic and geomagnetic coordinates with reference to the capital of each of the countries.

Table 1. African Countries within the Magnetic Equatorial Region and the Coordinates

S/N	Name of Country	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude/degree	Geomagnetic Longitude/degree
1	Benin	06°23'N	02°42'E	8.70N	76.57E
2	Cameroon	03°50'N	11°35'E	3.99N	84.80E
3	Central African Republic	04°23'N	18°35'E	4.07N	92.03E
4	Côte D'Ivoire	05°37'N	04°17'W	10.41N	67.87E
5	Ethiopia	09°02'N	38°42'E	5.36N	112.5E
6	Ghana	05°35'N	00°06'E	8.31N	73.96E
7	Liberia	06°18'N	10°47'W	10.70N	63.23E
8	Nigeria	09°05'N	07°32'E	10.52N	81.91E
9	Sierra Leone	08°30'N	13°17'W	13.23N	61.05E
10	South Sudan	15°31'N	32°35'E	12.68N	107.63E
11	Togo	06°09'N	01°20'E	8.66N	75.27E
12	Somalia	2°05'N	45°32'E	1.93S	118.22E

3. Scientific Objectives

There are a number of scientific objectives that will be addressed by the simultaneous use of the proposed instrumentation. A full discussion of the science is not possible here and hence we briefly itemise these objectives below.

- I. Study of the unique properties of the ionospheric irregularities over the African equatorial sector, leading to better understanding of the electrodynamics and the fundamental physics

responsible for the uniqueness in this sector. As indicated above, ionospheric irregularities over the African sector have been identified to be different from the ionospheric structures in other equatorial sectors (Burke et al., 2004; Amory-Mazaudier et al., 2005; Hei et al., 2005; Gentile et al., 2006; Yizengaw et al., 2013).

- II. Understanding the role of the African sector of the equatorial ionosphere in the formation of the global current system, thus enhancing our understanding of the global structure and the dynamics governing the equatorial ionosphere and the ionosphere as a whole.
- III. Understanding the contributions of the African equatorial sector in the formation of plumes, the mechanisms of these plumes, their spatial and temporal effects in this sector, and the determination of occurrence rates (Su et al., 2006). Gentile et al. (2011) using DMSP satellite data have shown that plasma bubbles observed in the African sector are stronger than at other longitudes.
- IV. Understanding how magnetic and ionospheric disturbances resulting from auroral phenomena extend on a planetary scale, and in particular to the equatorial region, over the solar cycle (see Cohen (1998)).
- V. Contribute to an understanding of why models fail to predict the unique structures of the equatorial ionosphere over the African sector, thus improving our capability of modelling plasma bubbles, modelling the global distribution of ionospheric and plasmaspheric density.
- VI. Understanding the ionospheric disturbances that affect the precision of navigation systems in the equatorial region of the ionosphere (Doherty et al., 2004; Kintner et al., 2009; Seo et al., 2011).
- VII. Understanding both the daytime and night-time ionospheric structures under different magnetic conditions (Hysell, 2000).
- VIII. Provide insight into the relationship between the occurrence of equatorial anomalies and ultra-low frequency (ULF) waves at low latitudes (Friedel et al. 2002).

- IX. Investigate whether the physics of the EEJ in the African equatorial sector is different from other sectors of the dip equator. Doumouya and Cohen (2004) have shown that there is a strong longitudinal variation in the formation and occurrence of the EEJ due to the dynamo electric field which drives the current resulting in regional variations in the equatorial ionospheric anomaly (EIA).
- X. Determination of whether there is a variation in the classes of irregularities associated with the EEJ in the African sector compared with other sectors of the equatorial ionosphere.
- XI. Is gravity wave driven instability the possible generation mechanism of field aligned plasma irregularities in the equatorial ionosphere?
- XII. Understanding the role of the African sector in our capability to nowcast, forecast, and predicts space weather events (Basu et al., 2002; Amory-Mazaudier et al., 2005).
- XIII. To compliment the results of the C/NOFS space mission in understanding the unstable scale sizes in which energy is injected into the region, the scales in which it is dissipated, the coupling of the scale sizes, and the wavelength regime in which the latter is accomplished (de la Beaujardière et al., 2004).
- XIV. To compliment the Ionospheric Connection (ICON) and the Global-Scale Observations of the Limb and Disk (GOLD) space missions in understanding the variability of Earth's thermosphere and ionosphere.

4. Instrumentation

The instrumentation proposed to address the above science objectives is in two parts, and will be designed such that they provide near-real time or real-time measurements and observations. The first is the use of a network of radars along the African sector which we refer to as the Africa Equatorial Radar Network (AfrequaRN). The network will be part of a proposed project consisting of an overall network of radars for the equatorial region covering the American, Asian, African, and Pacific sectors of the magnetic equator, termed the Equatorial (Dual) Electrojet Radar Network

(EquaERN (EquaDERN)), similar to the Super Dual Auroral Radar Network (SuperDARN) covering the high-latitude and polar regions (Greenwald et al., 1995; Lester et al, 2004, 2013; Chisham et al, 2007). SuperDARN has been in operation for over twenty years and has proved, and is still proving, to be one of the most successful ground-based instruments used to study the Earth's neutral atmospheric, ionospheric, and magnetospheric dynamics. An example of ionospheric convection measured by three SuperDARN high latitude radars (the Hankasalmi radar at 62.32°N 26.61°E, the Pykkvibaer radar at 63.77°N 20.54°W, and the Stokkseyri radar at 63.86°N 22.02°W, all with fields-of-view extending from magnetic latitudes $\sim 65^\circ$ towards the north pole) is presented in Figure 6a. These data are taken from McWilliams et al. (2001), and show the high latitude ionospheric response to high latitude dayside magnetopause processes. Similarly, data from Grocott et al. (2011) is shown in Figure 6b, presenting measured ionospheric convection from SuperDARN mid-latitude radars (the Falkland Islands radar at 51.8°S 59.0°W and the Blackstone radar at 37.1°N 78.0°W, with fields-of-view extending from magnetic latitudes $\sim 50^\circ$ to $\sim 80^\circ$). Here the response of the sub-auroral ionosphere to lower-latitude nightside magnetospheric processes is explored. Figure 6a and 6b demonstrate the strength of HF radars in measuring ionospheric convection in the polar and sub-auroral regions. AfrequaRN will allow the extension of these science goals to the low-latitude region providing, for the first time, a truly global picture of the ionospheric response to solar wind-magnetosphere-ionosphere coupling.

Figure 6. Ionospheric convection measured by (a) high latitude radars taken from McWilliams et al. (2001), and (b) mid-latitude radars taken from Grocott et al. (2011)

Plasma density irregularities in the equatorial ionosphere are field aligned, hence strongly aspect sensitive, such that the wave vector $\mathbf{k}_r$ of the proposed radars must be near-perpendicular to the magnetic field and equal to $\frac{1}{2} \mathbf{k}$ in order to satisfy the Bragg condition for coherent scatter, where $\mathbf{k}$ is the wave vector of the irregularities (Fejer and Kelly, 1980). These conditions are similar to density irregularities at auroral latitudes hence the well-known design and deployment mechanisms of the SuperDARN radars can be employed in the design and deployment of AfrequaRN. As is evident from Figure 4b, there is no radar instrumentation in the African sector of the magnetic equator at the present time.

Two major types of field-aligned irregularities have been identified in the African region by previous campaigns with a multifrequency HF radar installed in Ethiopia, East Africa in the 1970s (Hanuse and Crochet, 1977, 1979, 1981a, 1981b), and in Côte d'Ivoire, West Africa with the use of broad beam HF zenithal radar during IEEY campaigns (Farges et al., 1999). These irregularities have also been identified with incoherent backscatter radar at Jicarmaca, in the American region of the equatorial ionosphere (Bowles et al., 1963; Balsley, 1969; Fejer et al., 1975, Kudeki et al., 1987; Hysell et al., 2007). These irregularities are type I irregularities which are excited by the two-stream instability processes which has a velocity threshold requiring the drift velocity to exceed the

ion acoustic speed, and the type II irregularities associated with the gradient drift instability which has little or no drift speed threshold (Bowles et al., 1963; Fejer et al., 1975; Kudeki et al., 1987; Farges et al., 1999; Hysell et al., 2007). These two instabilities are also amongst the dominant mechanisms for the development of irregularities in the high-latitude ionospheric region which have been identified and studied with the SuperDARN radars (Milan and Lester 1999; Spicher et al., 2015), and observables between 1 m s^{-1} and 3 km s^{-1} (sub-meter to kilometre scale sizes).

Kelley (1989) noted that the measurement made at Jicarmaca, in the American region of the equatorial ionosphere, show that the radial velocity of type 1 instabilities lie in the range $360 \pm 60 \text{ ms}^{-1}$ while the average Doppler velocity of type 1 instabilities observed with the 50 MHz radar at Arecibo is 150 m s^{-1} (Riggin et al., 1986). In addition, Hysell et al. (1994) observed a Doppler velocity exceeding 1000 m s^{-1} both at Jicamarca and Kwajalein, while Milan and Lester (1999) measured the velocity of type 1 irregularities with SuperDARN radars and noted values near 400 ms^{-1} with a spectral width less than 200 m s^{-1} . The value obtained by Milan and Lester (1999) is close to that measured by the Jicarmaca incoherent backscatter radar (Bowles et al., 1963; Fejer et al., 1975, Hysell et al., 2007). Thus the expected velocities lie well within the range of capability of the proposed radar system.

The design and deployment of AfrequaRN will thus be similar in technical detail to the SuperDARN radars, a network of polar HF coherent radars but with a different experimental geometry. In order to achieve perpendicularity with the field, the radars in AfrequaRN should be pointed in the magnetic east-west direction (Fejer and Kelly, 1980). A straw-man field of view configuration of AfrequaRN is shown in Figure 7. In addition, we propose that for AfrequaRN the radar design should include a stereo mode that allows the radars to have the capability to run two different experimental modes simultaneously (Lester et al., 2004). Stereo was developed to provide flexibility of the SuperDARN radars and to improve temporal resolution. It consists of two radar channels, where each channel has the ability to transmit and receive independent signals at different frequencies, sharing common transmitters, antennas, and control system (Lester et al., 2004).

Stereo has an interface box termed the “BAS box” which adds arbitration logic to protect the system from requests to transmit on both channel A and channel B simultaneously. It also ensures that the Rx/Tx switch in each Stereo channel is set to transmit requests in both channels. In addition, the BAS box incorporates remote monitoring of potential conflicts that is detected by arbitration logic, the aggregated duty cycle, operating frequency, and beam direction.

Figure 7. Proposed geometry of AfrequaRN radars, Sierra Leone, Côte D'Ivoire, Nigeria and Ethiopia.

The data products from the proposed radar network are backscattered power (signal-to-noise ratio between 3 – 40 dB, proposed uncertainties ± 3 dB), line-of-sight (LOS) Doppler velocity $\sim \pm 3000 \text{ ms}^{-1}$ (proposed uncertainties in the range of $0.5 - 1.0 \text{ ms}^{-1}$), Doppler spectral width as a function of both height (range along each beam direction, $>200 \text{ ms}^{-1}$) and zenith angle (ψ). These are similar to those products from the HF radar operated by the CEA (Commissariat à l'Energie Atomique) in Africa during the IEEY campaign (Blanc et al., 1996; Cecile and Blanc, 1996; Cohen, 1998; Doumouya et al., 1998; Farges et al., 1999). The above data products in addition to the angle

of elevation (α) of the backscattered signals are also similar to the products from the SuperDARN radars (André et al., 1998; Yeoman et al., 2001; Yeoman et al., 2008; Ponomarenko et al., 2011; Bland et al., 2014) and to the pulsed HF Doppler radar at Visakhapatnam (17.7N 83.3E, geomagnetic dip 20) in India (Reddi et al., 2009). The products from the proposed radar network are capable of providing direct and inferred information, hence we also propose that some other ionospheric parameters, such as ionospheric critical frequencies, E region electron density, zonal winds in the electrojet region, the ambient zonal electric field and the ionospheric turbulence structure, Pedersen and Hall conductivities, horizontal electric current density, heat flux, temperature and velocity, neutral air density could also be inferred from the radar parameters (Hysell and Chau, 2001; Kudeki and Fawcett, 1993; Chau and Woodman, 2004; Shume et al., 2005b).

In addition, we propose the use of the following radar techniques among others in the investigation of the dynamics of irregularities in the African equatorial ionosphere, which includes oblique scattering, range-time-intensity (RTI) mapping, Faraday rotation, radar imaging techniques and multiple frequency scattering (Basu et al., 1978; Kudeki et al, 1981; Kudeki and Sürücü, 1991; Hysell and Woodman, 1997; Hysell and Chau, 2001; Hysell and Chau, 2006; Harding and Milla, 2013; Rodrigues et al., 2017). Table 2 shows the proposed scientific objectives and the proposed radar parameters (data products) to investigate the scientific questions.

Table 2. Scientific Objectives and Proposed Radar Parameters to be Measured

S/N	Proposed Science Objectives	Radar parameters (data products) to be measured (Direct/Inferred)
1	Study of the unique properties of the ionospheric irregularities	Radar backscattered power, LOS Doppler velocity, Doppler spectral width
2	The role of the African sector of the equatorial ionosphere in the formation of the global current system	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the elevation angle (α) of signals
3	The contributions of the African equatorial sector in the formation of plumes, the mechanisms of these plumes, their spatial and temporal effects in this sector	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and data from the magnetometers array

4	Understanding how magnetic and ionospheric disturbances resulting from auroral phenomena extend on a planetary scale	Radar backscattered power, LOS Doppler velocity, Doppler spectral width, and data from magnetometers array linked with other magnetometer array in Africa and Europe to monitor the ULF waves
5	Predicting the unique structures of the equatorial ionosphere over the African sector	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and modelling of equatorial parameters obtained from V/HF radars in different sectors
6	Investigate the ionospheric disturbances that affect the precision of navigation systems in the equatorial region of the ionosphere	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the elevation angle (α) of signals and data from the magnetometer array
7	Understanding both the daytime and night-time ionospheric structures under different magnetic conditions	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the elevation angle (α) of signals
8	The relationship between the occurrence of equatorial anomalies and ultra-low frequency (ULF) waves at low latitudes	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the data from the magnetometer array linked with other magnetometer arrays in Africa and Europe to monitor the ULF waves using similar methods proposed by Yizengaw and Moldwin, 2009
9	Investigate whether the physics of the EEJ in the African equatorial sector is different from other sectors of the dip equator.	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the data from magnetometers array linked with other magnetometer arrays in Africa and Europe to monitor the EEJ and modelling of equatorial parameters obtained from HF radars at different sectors
10	Variation in the classes of irregularities associated with the EEJ in the African sector compared with other sectors of the equatorial ionosphere	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and measurement of the ionospheric east-west electric field that drives EEJ current
11	Generation mechanism of field aligned plasma irregularities in the equatorial ionosphere	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the elevation angle (α) of signals
12	Understanding the role of the African sector in our capability to nowcast, forecast, and predicts space weather events	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the elevation angle (α) of signals
13	Understanding the variability of Earth's thermosphere and ionosphere	Radar backscattered power, LOS Doppler velocity, Doppler spectral width and the elevation angle (α) of signals

We propose four radars in this network, to be installed in Sierra Leone, Côte D'Ivoire, Nigeria and Ethiopia. We also propose that the radars in the network should be operated in pairs similar to the operation of some SuperDARN radars, such that the radars have overlapping fields of

view to enable the use of Doppler information from the backscattered signals to make velocity maps in the African sector of the equatorial ionosphere (Chisham et al., 2007).

The second phase of the proposed project is the installation of an array of magnetometers which is referred to as the Africa Equatorial Magnetometers (AfreqMAG). The magnetometers will be installed in each locality of identified countries within the African sector of the equatorial ionosphere. The data products to be measured are one minute geomagnetic daily variations of horizontal (H_{north} , D_{east}) and vertical Z components. Doing so will provide the science community with the ability to monitor the current systems that might lead to ionospheric irregularities over the region and will complement other instruments deployed in the region such as MAGDAS, SCINDA, and AMBER. We propose that ten magnetometers will be deployed in Sierra Leone, Liberia, Côte D'Ivoire, Ghana, Togo, Benin, Nigeria, Cameroon, Central Africa Republic, and Ethiopia. This two-in-one proposed instrumentation agenda is jointly referred to as the Africa Equatorial Magnetometer Array and Radar Network (AfrequaMARN). Deployment will provide simultaneous measurements of electric and magnetic fields in the African sector of the equatorial ionosphere.

5. Conclusions

The African sector of the equatorial ionosphere is the least studied by scientists due to the lack of ground-based instrumentation. It has been shown by satellite observations that the structure and dynamics of ionospheric irregularities in this sector are distinct when compared with other longitudinal sectors. Hence, there are a number of unanswered questions regarding the physics and dynamics of the equatorial ionosphere.

AfrequaMARN is a science project which consists of the deployment of a network of magnetometers (AfrequaMAG) and radars (AfrequaRN) to study and understand the ionospheric dynamics over the African sector. The proposed project will fill a significant gap in our global understanding of the physics of ionospheric plasma irregularities by providing the science

community with the opportunity to carry out long term altitudinal profiles of the ionosphere, leading towards understanding the distinct features of the African sector of the equatorial ionosphere, the mechanisms responsible for those features, understanding the role in balancing the global current system, and its contribution towards adequate nowcast, forecast and prediction capabilities of space weather.

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