The Equatorial Ionospheric Phenomena: a review of Past Studies, Government Interest and Unsolved Problems

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Abstract
The results from previous studies on ionospheric variability have shown that the ionosphere, especially over the equatorial and low latitude region undergoes sporadic changes in the electron density structure which causes harmful effects to high frequency satellite radio signals passing through the region. This paper attempts to review past work on the phenomena dominating the equatorial and low latitude ionosphere and to highlight yet unsolved problems. There are several attempts by past scientist to study and understand the dynamic structure of the ionosphere across different latitudes and longitudes using ground-based observations, in-situ satellite measurements and ionospheric models. These scientists have come up with reports of different anomalous phenomena dominating the equatorial and low latitude region. Some phenomena like the spread-F, equatorial electrojet current and equatorial anomaly have been highlighted. Apart from all the interesting reports so far documented, there are yet some grey areas that still needs further research. For example, the ionosphere-thermosphere coupling at equatorial and low latitude during extreme solar event and earthquake disaster is still a subject of major concern.

Keywords: Equatorial Ionosphere, Spread-F, Equatorial Electrojet, Equatorial Anomaly.

Resumen
Los resultados de estudios previos sobre la variabilidad ionosférica han demostrado que la ionosfera, especialmente sobre la región ecuatorial y de baja latitud, sufre cambios esporádicos en la estructura de densidad de electrones que provocan efectos nocivos en las señales de radio satelital de alta frecuencia que pasan por la región. Este documento intenta revisar el trabajo anterior sobre los fenómenos que dominan la ionosfera ecuatorial y de baja latitud y resaltar los problemas aún no resueltos. Hay varios intentos de científicos anteriores para estudiar y comprender la estructura dinámica de la ionosfera en diferentes latitudes y longitudes utilizando observaciones terrestres, mediciones satelitales in situ y modelos ionosféricos. Estos científicos han presentado informes de diferentes fenómenos anómalos que dominan la región ecuatorial y de baja latitud. Se han destacado algunos fenómenos como la propagación-F, la corriente de electrochorro ecuatorial y la anomalía ecuatorial. Además de todos los informes interesantes documentados hasta ahora, todavía hay algunas áreas grises que aún necesitan más investigación. Por ejemplo, el acoplamiento ionosfera-termosfera en latitudes bajas y ecuatoriales durante eventos solares extremos y desastres sísmicos sigue siendo un tema de gran preocupación.

Palabras clave: Ionosfera Ecuatorial, Spread-F, Electrochorro Ecuatorial, Anomalía Ecuatorial.

I. INTRODUCTION

The ionosphere is a region in the earth's upper atmosphere starting from 50km to about 1000km usually populated with free electrons. The process of photoionization [59] produces these free electrons. Photoionization is a process whereby X-rays and Ultra-Violet radiations from the sun collides with and knock-off electrons from the outermost shell of neutral particles lingering the region. This leaves behind a partially ionized region called the ionosphere. The interaction of the solar radiations with the complex physical and chemical compositions causes the ionosphere to be vertically divided into D, E and F layers. The free electrons in the ionosphere acts as potential threats to satellite radio signals propagating through it by causing effects such as diffraction, refraction, range error, amplitude and phase scintillation, Faraday rotation, waveform distortion, etc. Figure 1.1a shows the different ionospheric layers, while Figure 1.1b shows ionospheric effects on satellite radio signals.

This regions which suffers spatio-temporal variations is more complicated at equatorial and low latitude region (0 - ±20º Lat.) than the middle and high latitude regions. The complex nature of the equatorial and low latitude ionosphere have been attributed to the orientation of the geomagnetic field lines which are nearly horizontal. Scientist have and are still studying the behaviour of the ionosphere during quiet and disturbed geomagnetic conditions across different longitudes using different techniques and instruments, and their findings have established that the morphology of the ionosphere during quiet and storm-times are quite different.

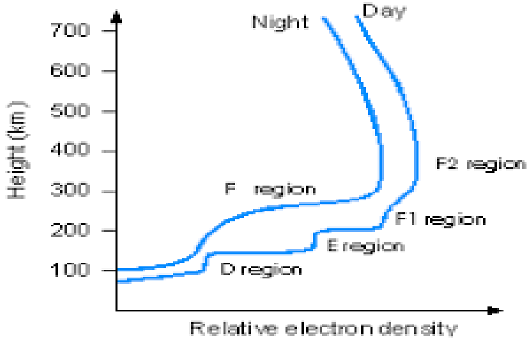


FIGURE 1.1a: layers of the ionosphere.

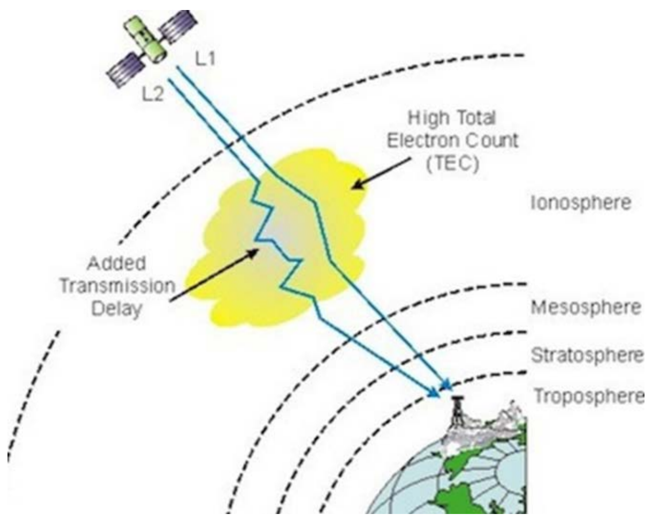


FIGURA 1.1b: Effect of the ionosphere on GPS signals (after [3]).

The studies are based on ground-based data, space-born observation data and ionospheric models. Ground-based ionospheric equipment such as ionosonde/digisonde, magnetometer, incoherent scatter radars, GPS receivers are mostly installed at American and Asian longitude than the African longitude, and hence the African longitude remains the least investigated by scientists. Also scientists from the American and Asian longitudinal sectors are more interested in ionospheric research because of the huge support and funding they obtain from their government and private sectors, in contrast to some parts in the African longitude where support and funding from government and private sectors are insufficient. The response of the Peruvian government, private sectors, scientists and students to the recent collapse of the Arecibo Observatory Radio Telescope after 57 years of commissioning will attest to our claim. Figure 1.2 shows the picture of the Arecibo Observatory Radio Telescope before and after collapse. While in some parts in the African longitudinal sectors, several ground-based ionospheric equipment have been abandoned for decades. A typical example is the ionosonde installed at the University of Ibadan, Nigeria which dis-functional early 1980s.

The equatorial and low latitude region are controlled by different equatorial phenomena such as the Spread-F, equatorial electrojet (EEJ) current and equatorial anomaly (EA), etc.

FIGURE 1.2: Image of the Arecibo Observatory Radio Telescope before collapse (left) and after collapse (right). The Arecibo Observatory Radio Telescope was commissioned 1st November, 1963 and collapsed 1st December, 2020.

II. SPREAD-F

One particular form of irregularity within the F region is called spread-F and this can impact High Frequency (HF) radio communication links. Spread F is an interesting phenomenon that can occur in the F region during the post sunset (evening period) and it's occurrences are more in the African longitudes [6]. Different mechanisms have been proposed to explain spread-F occurrences and their development [63]. Among these, the primary mechanism in equatorial regions is the generalized Rayleigh–Taylor (R–T) instability mechanism. The R–T instability mechanism suggests that pre-reversal electric field enhancements (PRE) during the evening cause a rapid uplift of the F-layer ionosphere [74].

One of the easiest method of detecting the actual state of the ionosphere above 100km altitude and deducing the effect it may have on HF radio communication is to use an instrument called ionosonde. This is an effectively HF pulsed radar system that uses the reflections from the ionosphere [1]. Spread F is normally defined in terms of the reflections received by an ionosonde and displayed on an ionogram (Figure 1.1).

The ionosonde transmits pulses up towards the ionosphere and normally an echo is returned and this has approximately the same length as the pulse that has been sent out. A small elongation of the pulse may be seen because the pulse is reflected back from a "spread" of different heights in the ionosphere. When Spread-F is present, echoes which are received back from ionosonde soundings indicate that there are irregularities in the F layer.

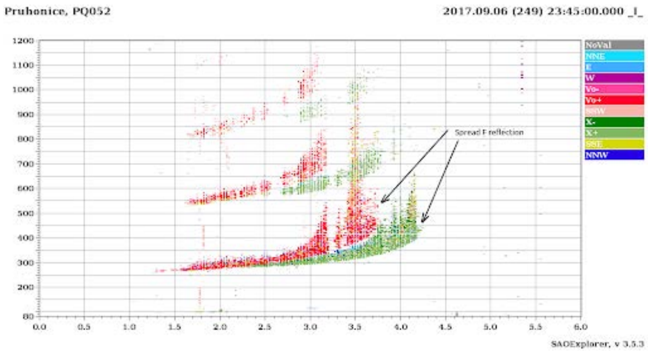


FIGURE 2.1: Spread-F ionogram observed at Pruhonice, Czech Republic.

Instead of receiving a defined echo to give the effective height of the ionosphere at that frequency, a diffused or fuzzy echo is received. Often the echo of the transmitted pulse received back at the ionosonde can be ten times the length of the transmitted pulse. There are three main types of spread that are seen on the ionogram when Spread-F is present. They are: Range spread (RSF), Frequency spread (FSF) and Equatorial spread (ESF).

When spread-F occurs, the F layer ionization becomes distorted (REFs), and appears as though turbulent showing different levels of ionization [4, 5, 35]. It can be described as plasma irregularities in the F region. The different ionized clouds or areas each reflect signals giving a variety of paths that the signal can take [2]. Around the equator between ±20°, equatorial Spread-F occur very frequently. In this region, equatorial spread-F is an evening and night time phenomenon. It can appear first near sunset, but it is most frequently observed between 21:00 and 01:00 local time, although it may appear earlier, especially at solar maximum.

The appearance of equatorial spread-F seems to correlate with the evening rise in the height of the F2 region [49]. There are few evidences of Spread-F occurrence at middle latitudes [32]. Spread-F are mostly equatorial and polar phenomenon [26]. Interestingly the occurrence of spread F differs between these two regions. In equatorial regions, Spread-F occur mostly on magnetically quiet days. While, at Polar regions, Spread-F is linked to a magnetic storm [20].

Some scientist in the past, for example: [20, 63, 39, 74] have tried to understand the evolution of Spread-F at different regions during both quiet and disturbed magnetic activity. [20] in early years introduced the concept of threshold virtual height (h′Fc) as a critical parameter controlling the day-to-day equatorial spread-F (ESF) variability. [74] reported that the movement of nighttime thermospheric neutral winds towards the equatorial ionosphere, which lowers **E**×**B** drift produces favorable conditions for instability development. The phenomenon of Spread F was reported to suffer spatio-temporal variations [2].

III. THE EQUATORIAL ELECTROJET (EEJ) AND COUNTER EQUATORIAL ELECTROJET (CEEJ)

The intense eastward ionospheric current that flows by day over a narrow latitudinal strip along the magnetic equator is known as the equatorial electrojet current [43]. In other words, it is an intense band of eastward electric current flowing within ± 3^o of the magnetic dip equator at 105 km altitude. The characteristic signature of the EEJ is a sharp negative V-shaped curve in the ΔH field, attaining its minimum within 0.5° of the magnetic dip equator and at noon local time. The universal solar-driven wind results in a solar quiet (Sq) current system in the E-layer of the earth’s ionosphere (100 – 110 km altitude). The Sq current in turn causes the generation of an eastward electrostatic field at the equatorial ionosphere, which is directed eastward during dayside. At the magnetic dip equator, where the geomagnetic field is almost horizontal, this electric field results in an enhanced eastward current (Pedersen current) flow along the magnetic equator. This **E**×**B** drift results in a downwards Hall current, sustaining vertical charge separation across the depth of the ionosphere, giving an upward secondary electric field and a secondary Pedersen current that is opposite to the primary Hall current.

A secondary Hall current then reinforces the original Pedersen current. At about 110 km height, the integration of the current density gives a peak current strength of about 100KAmps, which supports a day-side electrojet magnetic-field enhancement by a factor ~2 [25, 62, 17, 51]. This current is driven primarily by the E-region dynamo action of the neutral wind which is responsible for the strong enhancement in the horizontal (H) component of Earth's magnetic field observed by the magnetometers over equatorial regions as shown in Fig. 3.1.

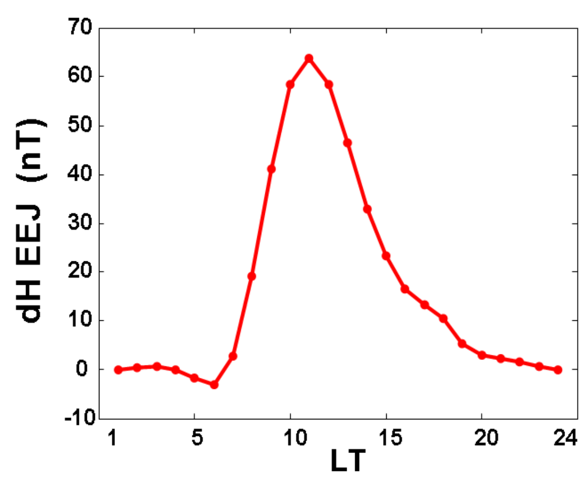


FIGURE 3.1: EEJ Magnetic Signal measured at Ettaiyapuram Magnetic Observatory, India. [ETT-Operated by National Geographical Research Institute, NGRI, Hyderabad].

The EEJ is different from the usual Sq current system and it is usually formed due to the distinctive geometry of the geomagnetic field at the equator. Since its detection, after the installation of a geomagnetic Observatory at Huancayo (Peru) near the dip equator, the EEJ has been the focus of many studies. Some theories and physical models of the ionospheric dynamo have been developed (e.g., [61, 62, [71], 12, 13] in order to explain the mechanism of the EEJ current flow and its main features, such as day-to-day and seasonal variability, counter-electrojet, electrodynamics processes of coupling with global-scale current systems, etc. The electric field or EEJ also suffers spatio-temporal variations. The EEJ is a consequence of the eastward E-region dynamo electric field and the unique horizontal structure of the geomagnetic field at the dip equator.

The equatorial electrojet (EEJ) current has been observed to reverse its normal direction and flows westward at night and during magnetically quiet and disturbed conditions. This reverse current system has been termed Counter Equatorial ElectroJet (CEEJ) by [34, 54, 27, 28, 29, 51]. The rapid reversal during disturbed conditions have been related to magnetospheric and high-latitude phenomena [43], whereas the reversal during quiet conditions have been related to lunar tides [55]. However, the exact physical mechanisms of CEEJ are yet to be completely understood.

Hence, there are some complications in its process of controlling the dynamics of low and equatorial ionosphere. Figure 3.2 shows the plots of the X-, and Y-field component of CEEJ observed at Trivandrum.

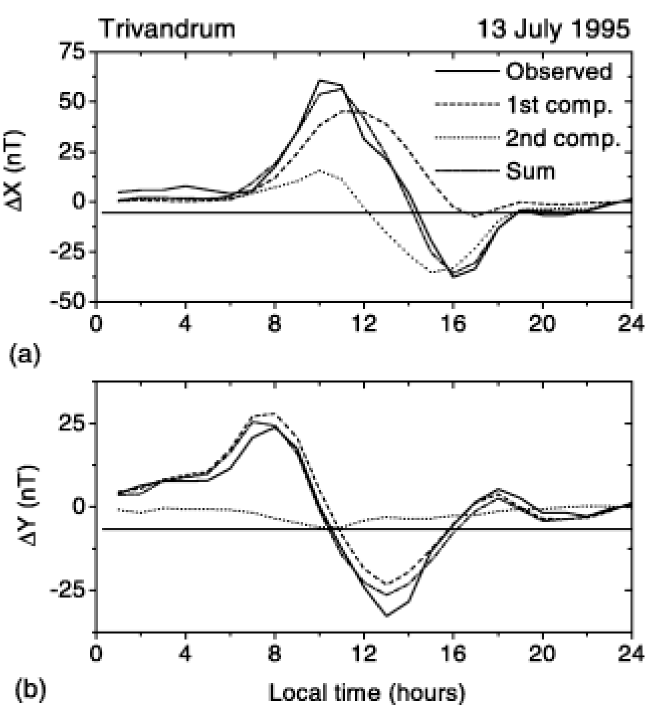


FIGURE 3.2: X-field and Y-field variations of Counter Equatorial Electrojet event measured at Trivandrum (after [31]).

Past studies on EEJ and CEEJ since their discoveries near the dip equator across different longitudes, have revealed that both phenomena display significant spatio-temporal variabilities [61, 38, 46, 30, 57, 58, 62, 56, 8, 47, 21, 22, 42, 50, 72].

The strength of the EEJ and its width have been established to change with longitude [69, 53, 36, 50] clearly revealed that along the African sector, the EEJ at the western sector appears weaker than the EEJ at the eastern sector. [72] reported higher values of EEJ and **E**×**B** drift distribution in the western American sector which decreases towards the eastern American longitudes all the way to the eastern African sector. [18] pointed that a few studies have reported that there is large day-to-day variability of the CEEJ phenomena over 45º longitude separation, which sometimes occurs over a wider longitudinal separation. [14] reported more frequent occurrence of daytime CEEJ events than nighttime CEEJ events at Ilorin in 2009. They attributed their findings to the late reversal of westward to eastward currents. [52] investigated the simultaneity and asymmetry in the occurrence of the CEEJ along African longitudes and most frequently found ~77% simultaneous occurrence of CEEJ during pre-sunrise at two extreme equatorial stations.

IV. EQUATORIAL ANOMALY (EA)

When the ionosphere is exposed to extreme space weather conditions, it undergoes changes which may cause serious threats to satellite communication and navigation systems [11]. This has become very important for the aeronomy scientific community for a proper understanding of ionospheric variability. The equatorial F2 region of the ionosphere exhibit variable characteristics based on electron density variations and solar zenith angle [19], thus making it the most anomalous and difficult region to predict. Some of the major equatorial F2 region anomalies are: seasonal, semi-annual, equinoctial asymmetry and equatorial ionization anomaly (EIA).

Seasonal anomaly is the highest/lowest electron densities in the June/December solstice respectively, in contrast to the solar zenith angle variation. Electron densities are usually higher in December than June solstice as a result of the changes in thermospheric composition caused by the dominant upwelling/downwelling of molecular/atomic rich air in June/December hemisphere respectively [60], [7].
Normally, when we follow the history of solar ionization, the ionization from the sun is expected to be higher in solstices (June and December) than equinoxes (March and September), but this is not the case. Solar ionization is usually higher in the equinoxes than the solstices. This phenomenon is known as semi-annual variation (semi-annual anomaly). It is caused by variations of the neutral wind in the thermoshere-ionosphere coupling which changes O/N_2 ratio [60, 7].

The equinoctial asymmetry is an equatorial phenomenon where the solar zenith angle and solar activities conditions show clear difference in March and September equinox. The unequal interplanetary conditions, solar flux, thermospheric neutral wind velocities in March and September equinox are the causes of equinoctial asymmetry [9, 40, 45].

The fourth equatorial anomaly is the equatorial ionization anomaly (EIA). The universal form of the equatorial and low-latitude region of the ionosphere is usually distorted with depletion of electron density over the geomagnetic equator and huge enhancements occurring around ±20° of the magnetic equator that corresponds to the EIA (Figure 4.1).

The EIA is controlled by the unique equatorial electrodynamics associated with electrojet (EEJ) and the Fountain effect. The Fountain effect is an electrodynamics lifting of the plasma which drifts upwards until the pressure and gravity force are huge enough to push the plasma back through the magnetic field lines to higher latitudes [10, 70]. This effect is the consequence of the fact that magnetic field lines run almost horizontally at the geomagnetic equator. The EIA is characterized by crests and troughs which are formed not only from accumulation of diffusing plasma [39], but also from the removal of plasma from around the equator by upward **E**×**B** drift [10]. The morphology of the EIA during quiet-time and storm-time which are quite different was well explained in [10]. [10] based their explanation on the electrodynamics drift theory of [44] and the diffusion theory of [48]. Another feature of the EIA is the nighttime ionization enhancement, which is a sudden increase in ionospheric electron density giving rise to increase in total electron content (TEC), critical frequency of the F2 layer (foF2), etc during the post-sunset hours [23, 24, 67]. Nighttime ionization enhancement have been attributed to the Pre reversal enhancement of the zonal electric field which is eastward-directed during the day and westward-directed at night. This phenomenon causes a sudden rise in the ionospheric electron density during post-sunset hours.

During daytime, the ionosphere normally has a uniform electron density distribution, whereby E region conductivity is active. This suppress ionospheric drivers such as thermospheric neutral winds and electric field fluctuation, and hence cannot generate ionospheric irregularities. During post-sunset, the E region conductivity becomes weak. This enhances the ionospheric drivers and hence generate plasma irregularities. Ionospheric irregularities which can manifest in different forms such as Spead F, plasma bubbles and optical images can causes amplitude and phase scintillation to high frequency radio signals when severe [15, 16, 65, 64].

These four equatorial phenomena have been documented in past research e.g. [60, 41, 45, 7, 37, 67, 70, 68] and many more.

Figure 4.2(a-c) shows the plot of ionospheric pierce point (IPP) total electron content (TEC) for African, Asian and American longitude EIA during the recovery phase of the June 1st, 2013 geomagnetic storm. The EIA for the three longitudes show distinct features during this period.

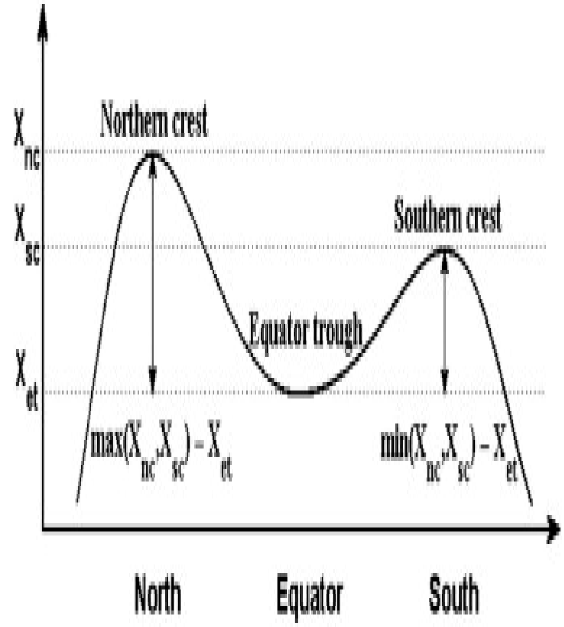
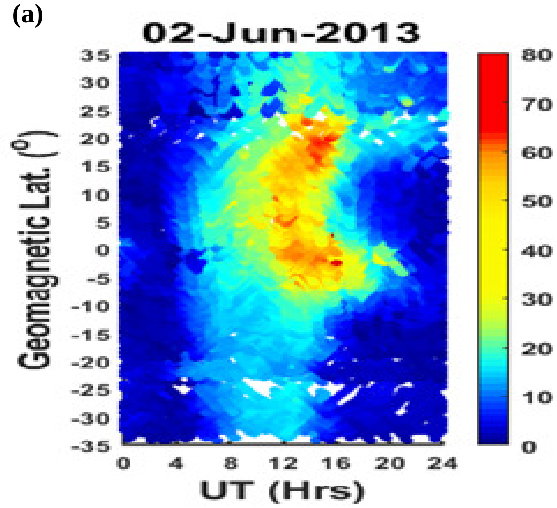
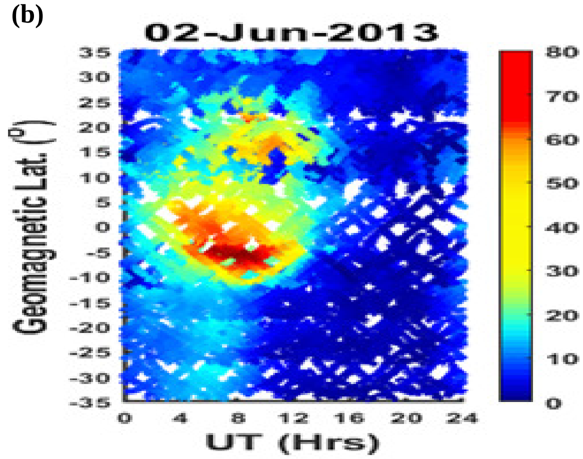


FIGURE 4.1: Illustration of the equatorial ionisation anomaly [after [33]].

(a)



(b)



(c)

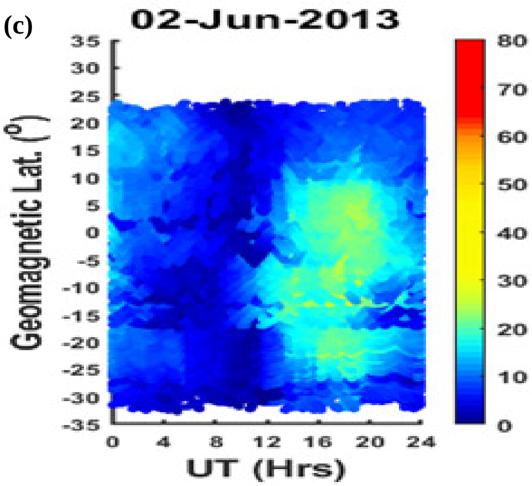


FIGURE 4.2 (a-c): Variations of IPP TEC maps for the African, Asian and American longitudes EIA respectively [after [70].

Multiple GPS receivers were used to compute IPP TEC maps in the three EIA longitudes. The EIA is observed in the Asian and American longitude, in contrast to the African longitude. The strong EIA in the Asian sector occurred before 12 noon and concentrated more at the south with a trough near -10º and weak EIA near the Northern crest. The weak EIA in the American sector occurred from 12:00 to post-sunset hour and covered from 10º – -25º latitude. Hence, EIA is observed to be stronger in the Asian longitude than the American longitude, and absent in the African longitude. There is also clear asymmetry in the Asian EIA than the American EIA [70].

V. UNSOLVED PROBLEMS

Irrespective of all the interesting findings in the equatorial region from past work, the ionosphere-thermosphere coupling at low latitude during extreme solar event is still a subject of major concern. At altitudes above 100km, thermospheric neutral winds and the electric current in the ionosphere which co-exist is still subject to question. A group of scientists are still trying to understand the dynamic nature of ionospheric irregularities which manifest as spread F, scintillation due to plasma bubbles and their mitigations, while some other groups of scientists are still trying to understand the ionspheric response during and after the occurrence of different magnitudes of solar flares and earthquake disaster. These statements conforms to [66], who reported that the spread F phenomenon and its seeding are complicated and have not been completely understood. The inclusion of spread F in ionospheric models is yet to be achieved. Also, the topside ionospheric electron density and its dynamics have not been accurately determined by ionospheric models, especially in the African longitude. The complex morphology of the ESF events and the diverse role of the different factors contributing to plasma irregularity initiation across the different longitudes is yet to be resolved [6]. Hence, there is need for further research at equatorial and low latitudes to strengthen the understanding of the observed inconsistencies in the ionospheric Space Weather events to know the possible ways to mitigate them in order to prevent damage to signals and man-made technologies.

VI. CONCLUSIONS

The equatorial and low latitude region of the ionosphere is the most problematic region of the ionosphere because of the complex E- and F-region electrodynamics taking place in it. The complex behaviour of this region poses different degrees of threats to high frequency satellite radio signals passing through it. The damage inflicted on the satellite signals are well monitored in the American and Asian longitudes as a result of government interest, other than some parts in the African sector, where the interest of government is very low. This paper highlights four major phenomena peculiar to the equatorial and low latitude region of the ionosphere. Although, these phenomena have been extensively studied in the past, but still there are some aspects that needs further attention which have been highlighted in section V.

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