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# Analysis of a grid ionospheric vertical delay and its bounding errors over West African sub-Saharan region

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A R T I C L E I N F O

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A B S T R A C T

Investigating the effects of the Equatorial Ionization Anomaly (EIA) ionosphere and space weather on Global Navigation Satellite Systems (GNSS) is very crucial, and a key to successful implementation of a GNSS augmentation system (SBAS) over the equatorial and low-latitude regions. A possible ionospheric vertical delay (GIVD, Grid Ionospheric Vertical Delay) broadcast at a Ionospheric Grid Point (IGP) and its confidence bounds errors (GIVE, Grid Ionospheric Vertical Error) are analyzed and compared with the ionospheric vertical delay estimated at a nearby user location over the West African Sub-Saharan region. Since African sub-Saharan ionosphere falls within the EIA region, which is always characterized by a disturbance in form of irregularities after sunset, and the disturbance is even more during the geomagnetically quiet conditions unlike middle latitudes, the need to have a reliable ionospheric threat model to cater for the nighttime ionospheric plasma irregularities for the future SBAS user is essential. The study was done during the most quiet and disturbed geomagnetic conditions on October 2013. A specific low latitude EGNOS-like algorithm, based on single thin layer model, was engaged to simulate SBAS message in the study. Our preliminary results indicate that, the estimated GIVE detects and protects a potential SBAS user against sampled ionospheric plasma irregularities over the region with a steep increment in GIVE to non-monitored after local sunset to post midnight. This corresponds to the onset of the usual ionospheric plasma irregularities in the region. The results further confirm that the effects of the geomagnetic storms on the ionosphere are not consistent in affecting GNSS applications over the region. Finally, this paper suggests further work to be investigated in order to improve the threat integrity model activity, and thereby enhance the availability of the future SBAS over African sub-Saharan region.

## 1. Introduction

Ionosphere and its variability remain a crucial issue for single-frequency Global Navigation Satellite Systems (GNSS) users worldwide for a critical application like air and maritime navigation. The situation could be worse at the equatorial and low-latitude regions (Prasad and Sarma, 2004) where the daytime ionization of electrons distribution is modified by the fountain effect, develops a crest at around $\pm 15^o to \pm 20^o$ magnetic equator depending on solar activity and season, and a trough at the magnetic equator during the late local noon. ICAO (International Civil Aviation Organization) Ionospheric Studies Task Force (ISTF/1)/1 (2012) edition of their white paper reported that GNSS implementation programs should take into account the potential limitations and disruptions of ionospheric effects to GNSS services. The white paper also stressed the fact of the existence of a peculiar ionosphere over the equatorial and low latitude regions, which could severely limit the availability of GNSS and its augmentation based Approach with Vertical guidance (APV) service in that region. Stoneback and Heelis, (2014) reported that ionosphere plasma density irregularities after sunset, and sometimes to post midnight at the equatorial region could be responsible for significant disruption to radio communication and navigation systems.

In order to support and enhance the satellite-based positioning navigation system with GNSS, American and European developed GNSS augmentation systems (SBAS, Satellite-Based Augmentation System) to cater for their regions using a single-shell ionospheric grid models. These allow the GNSS single-frequency users to correct errors due to ionospheric delay over Continental United State (CONUS) and European Civil Aviation Conference (ECAC) regions. The American and European SBAS are known as WAAS (Wide Area Augmentation System) and EGNOS (European Geostationary Navigation Overlay System) respectively. These systems were designed and built to

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compute and broadcast an estimated ionospheric delay at a predefined IGP over their regions for a safety-critical integrity that guarantees the reliability of the information being broadcast to the GNSS users. It is worth noting that CONUS and ECAC regions are within the middle latitude regions, in which the ionosphere is less complex in comparison to the low latitudes and Equatorial Ionization Anomaly (EIA) regions. In addition, the WAAS and EGNOS algorithms are based on single thin-shell layer model in which a fixed height is assumed where the ionosphere is represented as a thin layer.

Moreover, Indian subcontinent engaged a Multi Layer Data Fusion (MLDF) algorithm to build an augmentation system known as GAGAN (GPS Aided Geo Augmented Navigation), this is to cater for the effect of the complexity in equatorial ionospheric gradient delay on critical-GNSS applications such as civil aviation. The use of MLDF algorithm provides more robustness to the complexity of horizontal gradient variability peculiar to the EIA region ICAO, (2001); Suryanarayana Rao, (2007); Cezón et al. (2013) reported the description of the main limitations for SBAS technologies in the low latitude regions using Latin-American region as a case study and suggested the strategy to mitigate the effects of low latitude ionosphere on SBAS systems. It is to be noted that large percentage of Latin American region and the Indian subcontinent lie in the equatorial and low latitude region and that ICAO has currently certified the Indian SBAS system for APV-I level of service. Details could be found in and the ICAO publications (Sunda et al., 2015).

The broadcast integrity parameters consist of UDRE (User Differential Range Error) and GIVE (Grid ionospheric Vertical Error). UDRE is the residual error bound on the satellite orbit and clock corrections and the GIVE provides a bounding on the residual of the GIVD error over a 5°x5° grid of IGPs (Comier and Alsthuler, 2004). GIVE could as well be interpolated from the IGP to the nearby IPPs (Ionospheric Pierce Points), given reliability to the ionospheric vertical delay error of the user's IPP. This is known as User Ionospheric Vertical Error (UIVE). GIVE and UDRE bounds are used to calculate the confidence bounds of the positional error known as Horizontal Protection Levels (HPLs) and Vertical Protection Levels (VPLs) (ICAO, 2001). Prasad and Sarma (2007) defined GIVE as a tolerance value estimated on the delay at IGP, and it is the maximum error bounding the IGP (Conker et al., 1997). GIVE is a function of the IPP density and the variations of its delay measurements, including the spatial and temporal decorrelation of the ionosphere surrounding the IPP. Several ionospheric models have been used by (Walter et al., 2001; Sarma et al., 2006, 2009; Venkata Ratnam et al., 2009, 2011) to investigate the GIVD and GIVE behavior under various geomagnetic conditions. Venkata Ratnam et al. (2011) reported that, all the models used followed the same trend, and that there is enhancement in GIVE values and reduction in ionospheric vertical delays at the IGP during all the geomagnetically disturbed conditions analyzed. However, their results indicate that the Modified Planar Fit Model (MPFM) provides better ionospheric delay under severe geomagnetic conditions but less SBAS (Satellite Based Augmentation System) availability. While the Minimum Mean Square Estimator (MMSE) model shows better SBAS system availability because MMSE algorithm is independent from the number and location of the nearby IPP.

It is worth noting that all the analyses in both theoretical and experimental done so far have been in the American, European and Asian regional sectors (Rama Rao et al., 2006; Seo et al., 2011; Sparks et al., 2011; Sunda et al., 2013; Cezón et al., 2014.) including Indian sub-continent where the ionosphere is more complex than African sector. Little or none could be said about the ionospheric corrections and its integrity error bounds over the IGPs within the African sub-Saharan region. One of the reasons is because of the non-existence of the operational SBAS system in the region. Secondly, there are no publicly available stations designed for such study. And if the ionospheric correction and its bounding error algorithm of the present EGNOS or WAAS are directly applied to the African sub-Saharan region's SBAS without any modification, it may be difficult to realize the optimum performance in terms of availability and bounding integrity. This work used experimental GNSS data from public available geodetic stations to simulate a potential SBAS system performance over the West African sub-Saharan region, using a specific low latitude algorithm based on single layer model. The first task was to preprocess the data to meet SBAS requirements sampling rate. In order to estimate the variability of the GIVE and GIVD in relation to the complexity of ionospheric irregularities activity, the most geomagnetically disturbed and quiet conditions of the equinoctial month of October 2013 are used. Section 2 contains the conventional method of estimating GIVD and GIVE at a specific IGP at the center of the service area. Section 3 describes the results of the GIVD and GIVE at the IGP analyzed, in relation to the plasma irregularities and the estimated vertical delay of a user close by. Section 4 discusses the summary and the conclusions of the study. The preliminary results of the study could provide an insight as well as a guide to the successful implementation of SBAS system in the region.

## 2. Data source and ionospheric delay estimation

### 2.1. Data source and analysis

GIVD is the ionospheric delay obtained through a grid model at a standard predefined point of 5°x5° degree within low and middle latitude, specifically designed for ionospheric corrections in GNSS augmentation system like SBAS. At the same time, GIVE has been defined as a bound ionospheric correction error over the estimated GIVD at each IGP. In order to estimate the possible GIVD and GIVE at the IGPs over the West African sub-Saharan region, experimental data from 10 GNSS stations through IGS (International GNSS Services) network and other public available networks (AFREF, NIGNET, SONEL) primarily meant for geodesy in the region are engaged in the study. The detail of the stations used and its spatial distribution are shown in Fig. 1. To meet the SBAS requirements, the 30 s interval data rate obtained in these networks are preprocessed to 1-second interval data rate using Lagrange interpolation method. Lagrange interpolation is polynomials based interpolation techniques that give non-monotonous outputs; details could be obtained in Jeffreys and Jeffreys, (1988). The SBAS simulator (magicSBAS), containing a specific low latitude algorithm acquired by ICTP for the purpose of TREGA (Training on EGNOS-GNSS in Africa) project is used for the SBAS message emulation. Details of magicSBAS could be obtained from Cezón et al. (2014). The 10 GNSS stations are used as a potential network of RIMS (Ranging Integrity Monitoring Stations). A static user at Accra (5.55°N; 0.20°W) close to the IGP (5°N, 0°E) was used to evaluate the values of GIVD and GIVE over the region.

### 2.2. Estimation of GIVD and GIVE

To compute GIVD over the IGP, the slant ionospheric delays at the IPPs near the IGP are first obtained. The IPPs are the points where the ray-path between the satellite and the ground receiver penetrates the ionosphere at the assumed height of 350 km, where the ionosphere is represented a thin layer. The delay along that path is known as slant delay, and it is estimated using the dual-frequency measurements (Eq. (1)). The vertical equivalent of this delay is obtained by multiplying the slant delay by the mapping function (Eq. (2)). However, the mapping function (Eq. (3)) could introduce error up to 2–3 ns.

$$sD=\frac{C\gamma f_2^2}{(f_2^2-f_1^2)} \tag{1}$$

$$vD=sD\times MF \tag{2}$$