International Beacon Satellite Symposium BSS-2016
Trieste, Italy

Equatorial Plasma Bubble Effects on Ground-Based Augmentation Systems and Its Mitigation Techniques

Jiyun Lee*[1], Moonseok Yoon[1], Dongwoo Kim[1] and Sam Pullen[2]

[1] Department of Aerospace Engineering, KAIST, Daejeon, Republic of Korea.
(E-mail: jiyunlee@kaist.ac.kr, moonseokyoon@kaist.ac.kr, hiroo@kaist.ac.kr)

[2] Department of Aeronautics & Astronautics, Stanford University, CA, USA.
(spullen@stanford.edu)

ABSTRACT

Equatorial ionosphere situated within 25 degrees latitude of the magnetic equator is known to be significantly more intense and unpredictable than what is encountered (and has been extensively studied) in mid-latitude regions such as the Conterminous U.S. (CONUS). Ground-Based Augmentation Systems (GBASs) that enhance the performance of Global Navigation Satellite Systems (GNSSs) must be robust to all possible ionospheric threats to avoid hazardous errors and frequent service interruptions. Hence, we have studied anomalous ionospheric behavior and assess their effects over the Brazilian region for the current Solar Cycle #24 to support GBAS operations in this region.

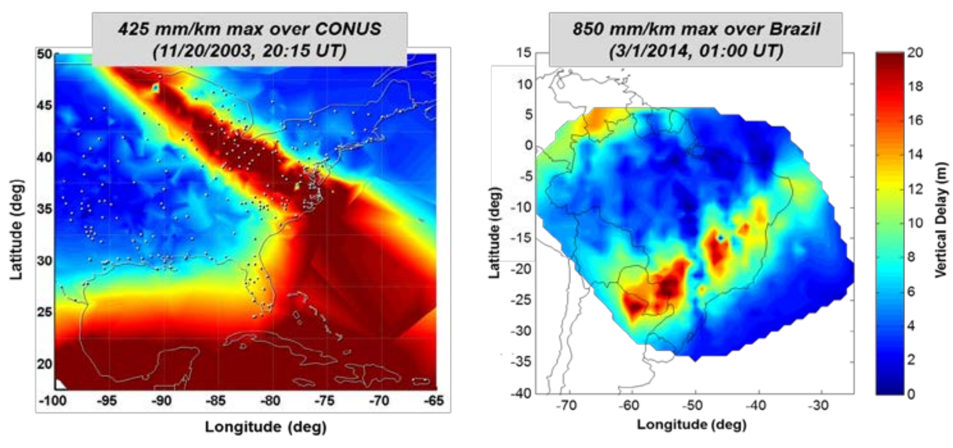

Figure 1. Two different ionospheric anomaly events: Storm Enhanced Density (SED) in CONUS (left) versus Equatorial Plasma Bubble (EPB) in Brazil (right)

Prior work has developed the new GBAS ionospheric threat model which reflects Brazilian low-latitude ionospheric conditions [1]. Dual-frequency GNSS data collected over about 120 active ionosphere days was utilized to identify over 1000 anomalous gradients from post-processed data. Because erroneous measurements, such as post-processing errors and receiver/satellite faults, can create large gradients appearing where none actually exist, we further validated these gradients to be real using the method proposed in [2]. Through comprehensive analysis, we confirmed that almost all of these were caused by night-time Equatorial Plasma Bubbles (EPBs). A significant number of ionospheric gradients exceed the upper bounds (375 – 425 mm/km) of the CONUS threat model [3]. In particular, the largest gradient of about 850 mm/km is twice as large as the maximum gradient observed in CONUS.

The spatial and temporal characteristics of anomalous ionospheric events observed in CONUS (left) and Brazil (right), which produced severe ionospheric gradients, are different as shown in Figure 1. Hence, we also defined a series of threat model parameters to model the geometry of EPBs in the Brazilian region. The observations from Brazil were examined in detail to quantify both existing parameters used to model ionospheric storms in mid-latitude regions and newly introduced parameters for EPBs. A maximum depletion of 35 meters and transition zone lengths of between 20 and 450 km have been estimated for EPBs which produced the most extreme gradients. These EPBs appeared to be moving roughly eastward and parallel to the geomagnetic equator with speeds of between 40 and 250 m/s. Almost all significant EPBs occurred during post-sunset hours. These parameters were incorporated into the EPB threat model in order to assess the EPB impacts on CATegory-I (CAT-I) GBAS availability.

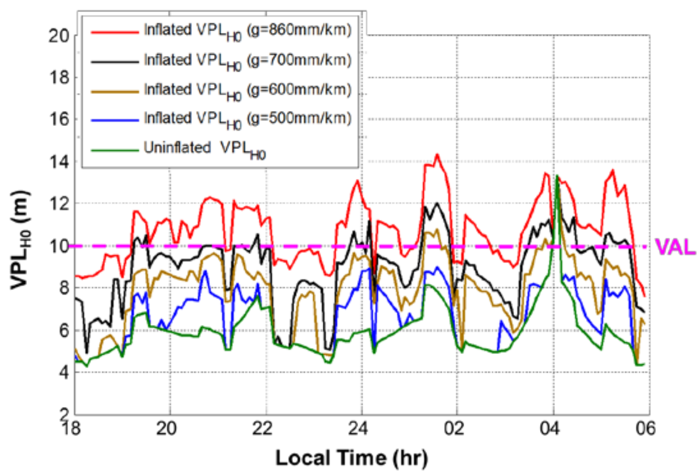

Figure 2. Inflated VPL_{H0}, nominal VPL_{H0}, and VAL at 6-km DH using the PDGS mitigation method.

We first assessed the performance of GBAS with Position Domain Geometry Screening (PDGS), which has been used in CONUS [4]. Using the parameters of the preliminary EPB threat model, sets of worst-case geometries among an EPB gradient front and satellite Lines-of-Sight (LOSs) are generated. Based on the scenarios, we analyzed the performance of GBAS under worst-case ionospheric conditions. Figure 2 shows the inflated Vertical Protection Level (VPL) at 6-km Decision Height (DH) during the nighttime. The different colors of the solid curves indicate the different size of the maximum gradient bound applied to EPB impact simulations. As the maximum gradient bound increases during the nighttime, the margin between VPL and Vertical Alert Limit (VAL) become smaller due to higher sigma inflation required. In particular, when the gradient bound is 860 mm/km (red curve), the inflated VPL_{H0} (red solid curve) significantly exceeds VAL. These results imply that with an elevated gradient bound greater than about 500 mm/km, it is difficult to meet the CAT-I availability requirement at 6-km DH using the current PDGS method.

For this reason, we also employed Monte Carlo analysis [5]. The key difference from the previous approach is that credit is taken for a prior probability of an extreme EPB event instead of assuming that worst-case storms occur with a probability of one in PDGS. This stochastic approach assesses the overall user impact by running many anomalous ionospheric trials based upon numerous combinations of threat model parameters. For each subset geometry, it is assumed that either one or two satellites are affected by the worst-case gradient while the remaining satellites are affected by anomalous but non-worst-gradients. Therefore, the worst-case impact should be approximated by inclusion in the distribution of simulation results. The resulting distribution of ionosphere-induced vertical errors at a 6-km DH implys that if we assume a total allowed (sub-allocated) integrity risk of 10^{-8}, the prior probability would need to be no greater than 10^{-6} or 10^{-7}. Unfortunately, while extreme EPB events in Brazil are uncommon, they are significantly more likely than this. Thus, a real-time mitigation scheme based on the Monte Carlo method, which also requires sigma parameter inflation, is proposed that takes credit for the prior probability. System availability evaluation using the Monte Carlo approach shows that the availability penalty is significantly reduced compared to the previous (worst-case) method.

The EPB impact scenario uses the constant gradient bound. From the preliminary analysis of the EPB behaviors, the gradient magnitude appeared to be dependent on elevation angle as well as azimuth angle. Hence, we analyze results when modeling the gradient bounds in terms of both angles. Furthermore, in the Monte Carlo-based ionospheric threat mitigation, it is important to estimate and justify a probability of extreme ionospheric gradients. Thus, we utilize the distribution of spatial gradients obtained from the Brazilian GNSS station data to estimate the likelihood of anomalous spatial gradients.

Key words: Ground-Based Augmentation System, Ionospheric Spatial Decorrelation, Equatorial Plasma Bubble, Ionospheric Anomaly Threat Model, Ionospheric Threat Mitigation.

References:

[1] J. Lee, M. Yoon, S. Pullen, J. Gillespie, N. Mathur, R. Cole, J. Rodrigues, P. Doherty, and R. Pradipta, Preliminary Results from Ionospheric Threat Model Development to Support GBAS Operations in the Brazilian Region," Proceedings of ION GNSS+ 2015, Tampa, Florida, Sept. 2015

[2] Yoon, M., Kim, D., Lee, J., and Pullen, S., Multi-dimensional Verification Methodology of Ionospheric Gradient Observation during Plasma Bubble Events in the Brazilian Region, Proceedings of the ION 2015 Pacific PNT Meeting, Honolulu, Hawaii, April 2015, pp. 748-762.

[3] Datta-Barua, S., Lee, J., Pullen, S., Luo, M., Ene, A., Qiu, D., Zhang, G., and Enge, P. (2010), Ionospheric Threat Parameterization for Local Area Global-Positioning-System-Based Aircraft Landing Systems, Journal of Aircraft, vol. 47, no. 4, pp. 1141-1151

[4] Lee, J., Seo, J., Park, Y., Pullen, S., and Enge, P., (2011), Ionospheric Threat Mitigation by Geometry Screening in Ground-Based Augmentation Systems, AIAA Journal of Aircraft, Vol. 48, No. 4, pp. 1422-1433

[5] M. Yoon, D. Kim, J. Lee, S. Rungraengwajiake, and S. Pullen, Assessment of Equatorial Plasma Bubble Impacts on Ground-Based Augmentation Systems in the Brazilian Region, Procedding of the ION ITM 2016, Monterey, CA, Jan. 2016