Ionospheric Storm and Spatial Gradient Analysis for GBAS

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Abstract

High ionospheric spatial gradient during ionospheric storm is most concern for the landing approach with GNSS (Global Navigation Satellite System) augmentation systems. In case of the GBAS (Ground-Based Augmentation System), the ionospheric storm causes sudden increase of the ionospheric delay difference between a ground facility and a user (aircraft), and the aircraft position error increases significantly. Since the ionosphere behavior and the storm effect depend on geographic location, understanding the ionospheric storm behavior at specific regional area is crucial for the GNSS augmentation system development and implementation. Korea Aerospace Research Institute and collaborating universities have been developing an integrity monitoring test bed for GBAS research and for future regional augmentation system development. By using the dense GPS (Global Positioning System) networks in Korea, a regional ionosphere map is constructed for finding detailed aspect of the ionosphere variation. Preliminary analysis on the ionospheric gradient variation during a recent storm period is performed and the results are discussed.

Keywords: Ionosphere, Ionospheric storm, Ionospheric spatial gradient, Ionospheric map, GBAS, SBAS

1. Introduction

Ionospheric storm, which is caused by the interaction between the solar and geomagnetic activity, changes ionospheric delay on the GNSS (Global Navigation Satellite System) signal rapidly. The most critical problem of implementing satellite augmentation systems, e.g. GBAS (Ground-Based Augmentation System) or SBAS (Space-Based Augmentation System), is the loss of integrity and availability during the ionospheric storm. In case of the GBAS, the storm radically increases the ionospheric delay difference between a ground facility and a user (aircraft), and the position error of the aircraft increases dramatically even with the correction signal [1,2].

In order to mitigate this problem, many researchers have been working on analyzing the behavior of the ionosphere and ionospheric storm [3]. Analyses on the storm effect on the GBAS/SBAS are based on these researches. The most key area of the research is the spatial gradient change of the ionospheric delay during the storm. The ionospheric storm increases spatial decorrelation and this level of decorrelation is represented as the ionospheric gradient. The ionosphere behavior and the storm effect depend on geographic location, especially geomagnetic latitude, since the ionosphere activity mainly depends on the geomagnetic activity. For this reason, understanding the ionospheric storm behavior at specific regional area is crucial for the GNSS augmentation system development and implementation.

Korea Aerospace Research Institute and collaborating universities have been developing an integrity monitoring test bed for GBAS (Ground-Based Augmentation System) research and for future regional augmentation system development. By using the dense GPS (Global Positioning System) networks in Korea, a regional ionosphere map is constructed for finding detailed aspect of the regional map. The ionospheric gradient variation during the storm period is analyzed. This paper reviews the effect of the ionospheric storm on GBAS and research topics for analyzing the effect. The methodology for computing the ionospheric gradient is discussed and the preliminary results on the ionosphere maps and gradient during a recent storm period are discussed.

2. Ionospheric Storm Effect on GBAS

GBAS ground facility (GGF) computes the correction for the raw GNSS signal and predicts the error level of various error sources on the signal. GGF broadcasts the signal to aircrafts and then the aircrafts correct their received GNSS range signal and computes the protection level (PL) of their computed positions [1]. The PL consists of VPL (Vertical PL) and HPL (Horizontal PL) and covers the error bound of the computed position. If the PL exceeds the pre-defined AL (Alert Limit) in either vertical or horizontal direction, the aircraft GBAS alarm system is activated and the correction information is not used. This case represents the loss of availability. CAT-I (Category-I), one of the requirements for precision approach and landing, specifies the VAL as about 10m. If the PL is set to high enough, then the integrity of the GBAS is increased while the availability is decreased. On the other hand, if the PL is set to low, then the availability is increased but the integrity is decreased. Finding the optimal PL, which should be the minimum value bounding the actual position error level, is the most critical research topic on the augmentation system developments.

The ionospheric storm causes abrupt change of the ionospheric signal delay in time and in space. Between the time-varying characteristics and the spatial decorrelation characteristics, the latter affects GBAS performance more significantly since GBAS broadcast the correction signal with high rate, 2Hz, and the time varying characteristics can be reduced. The spatial decorrelation causes the correction information received by aircrafts to be far deviated from actual range error [2].

In order to mitigate the high spatial decorrelation due to the ionospheric storm, GBAS broadcast message includes a ionosphere gradient estimation value, called σ_{vig} [1]. Using this value, the aircraft computes the error bound due to the ionosphere correction. One of the problems is how to sense the ionosphere gradient. When SBAS is available in addition to GBAS, the ionosphere gradient information can be obtained from the SBAS map. If GBAS is operated stand alone, several methods can be considered.

One is differentiating the satellite range signal in time. Since the satellite moves during the differentiation interval, the IPP (Ionosphere Pierce Point) or the location where the signal propagates the ionosphere layer is moved. The ionosphere delay change represents the spatial ionospheric gradient although it includes time varying signal as well [5].

Another method is using remote GNSS receiver(s), called LBM (Long Baseline Monitoring). When an LBM is installed along the runway, apart from the GGF, and the LBM provides the ionospheric delay information at the remote location, the ionospheric gradient between the two points can be computed. While the LBM approach provides more accurate information than the time differentiation method, it requires additional receivers and communication facilities. Other shortcoming is that the LBM detects the gradient along the GGF-LBM direction only.

2. Analysis Methodology

2.1 Ionosphere Map

Ionosphere signal delay map is classified into two categories, function based and grid based. The function based map assumes the distribution of the signal delay as a function of geographic location and time [6]. Ionosphere signal delay measurements are converted into vertical delay measurements at certain IPP and a pre-defined function is fitted with the measurements. The grid based map defines grid points with regular distance and maps the ionosphere delay measurements around the grid points into a single value at the grid.

The function based map is good to represent overall ionosphere variation but hard to represent local or temporal variation in detail. Since the function based map is better in rejecting measurement noise, it is good for estimating the inter-frequency bias (L1-L2). The grid based map is good to represent local variation with small size grid. However, in case of small size grids, there exists certain grid area where no measurements are available for certain period due to the geometry between the GNSS satellites and receivers. It is possible to combine the two methods, e.g. the function map for the bias estimation and the grid map for the ionosphere delay distribution.

2.2 Ionosphere Spatial Gradient

In order to analyze the effect of the ionosphere storm on GBAS, analysis on the ionosphere gradient variation during the storm is necessary. Method of computing the ionosphere gradient may includes: (1) Computing gradient from ionosphere map (2) Direct differentiation between two receivers' ionospheric delay signal for a common satellite [3,4,5].

The first method uses the grid based map data. The ionospheric delays at two adjacent grid points are differentiated along north-south and east-west direction. The second method differentiates the ionospheric delay measurements between two receiver pairs:

$$\left(g_{ij}\right)_{NS} = \frac{VTEC_i - VTEC_j}{d_{ij}} Cos\left(AZ_{ij}\right) \qquad (1)$$

where $VTEC_i$ is the vertical TEC measured by the i-th receiver and d_{ij} is the distance between the i-th and j-th receivers. In order to classified the gradient in the north-south and east-west directions, the measured gradient is mapped using the azimuth angle AZ_{ij} and $\left(g_{ij}\right)_{NS}$ represents the ionosphere gradient along the north-south direction between the i-th and j-th receivers. The east-west gradient, $\left(g_{ij}\right)_{EW}$, has the same form except the cosine term.

The gradient increase is caused by receiver noise or error as well as the ionosphere delay difference. In case of the first (grid) method, the effect of the receiver noise is not significant since the ionosphere delay at the grid points are already averaged values and it mitigates the noise. The second (differentiation) method's output is closer to actual ionospheric gradient but more sensitive to the receiver noise. Therefore, the first method is good for finding overall trend while the second method is good for finding detailed gradient variation especially during the storm event. Also, the differentiation method is good for real time implementation.

3. Data Analysis Results

3.1 Ionosphere Map

The solar activity was high around year 2001 and one of recent severe storms occurred in October and November 2003. This paper focuses on November 20, 2003 storm, which is one of the most severe ionosphere storms occurred (storm day), and October 27, 2003, which is just before another severe storm occurred (as a reference for a quiet day). The ionosphere behavior above Korean peninsular during these periods was analyzed. GPS observation data by Korea National Geodetic Institute (NGI) was processed. 14 stations provided 30s RINEX data using TRIMBLE 4000SSI receivers.

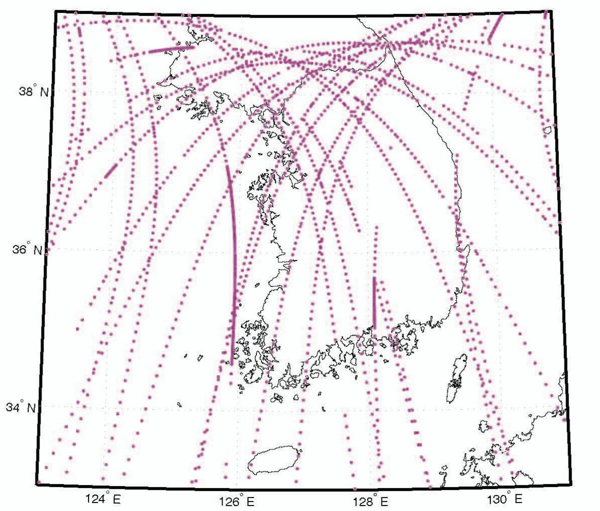

Figure 1 IPP locations (SUWN) - 2003.11.20

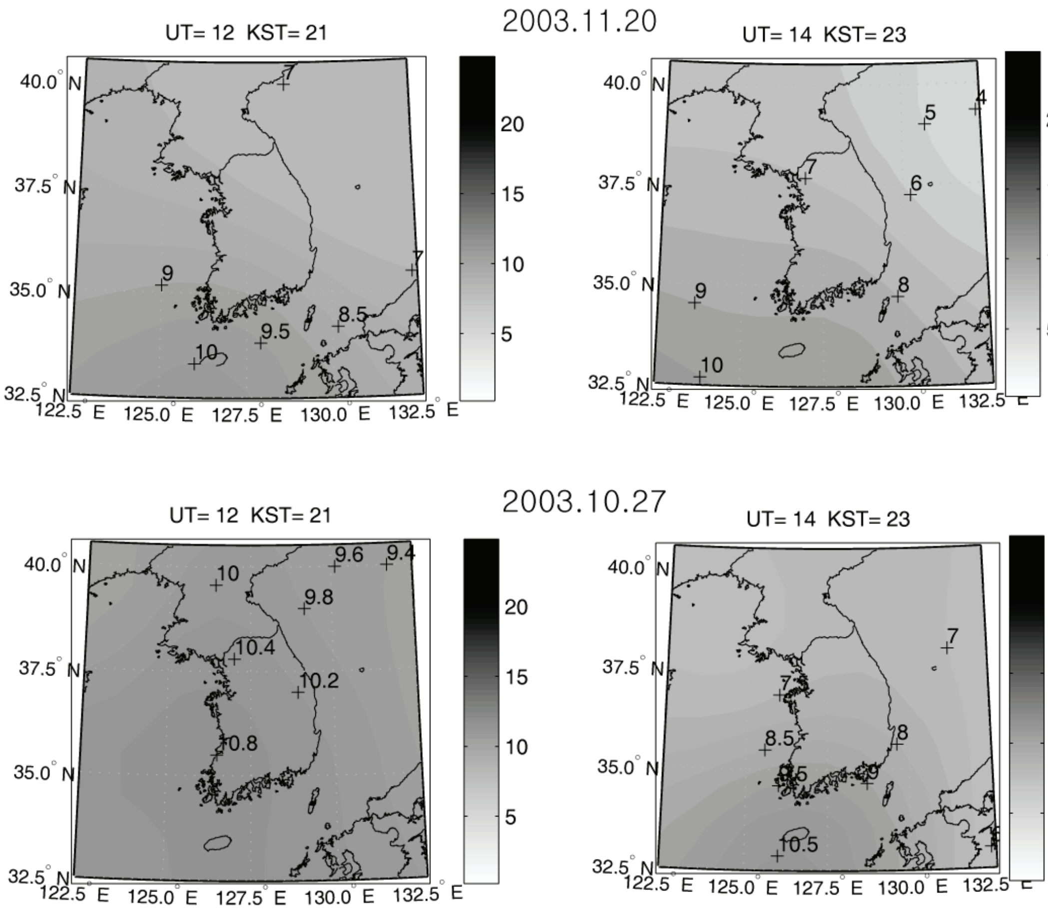

Figure 2 Ionosphere maps in a storm day (2003.11.20) and a quiet day (2003.10.27)

The inter-frequency biases were estimated with the function base map method. Bias for each satellite-receiver pair was estimated. With these estimated biases, the GPS code measurements are de-biased, and then the grid based map was computed.

Figure 1 shows the IPP locations of the GPS signals received by NGI SUWN station, which is an IGS station, in November 20, 2003. Relatively dense network of 14 stations provides dense IPP locations during the day, but for certain period no data grid still exist.

The grid based maps were computed using 1°×1° grid size. Figure 2 shows the ionospheric maps for November 20, 2003 and October 27, 2003. An analysis shows that the storm effect occurred during UT 12~14hr around Korean peninsular in November 20, 2003. Two time sets of UT 12 and 14 were chosen for comparison. Since the corresponding local time (KST) is night (KST 21~23hr), when the ionospheric delay itself is lower than the day time, the storm effect is not significant. A slight difference is high gradient during UT 14 of November 20.

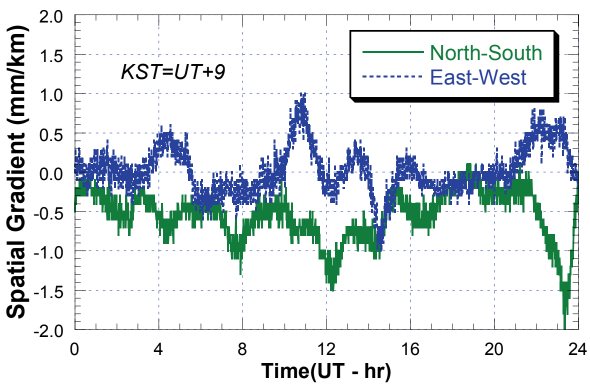

Figure 3 Ionosphere delay gradient variation in 2003.11.20 (grid map differentiation - code only)

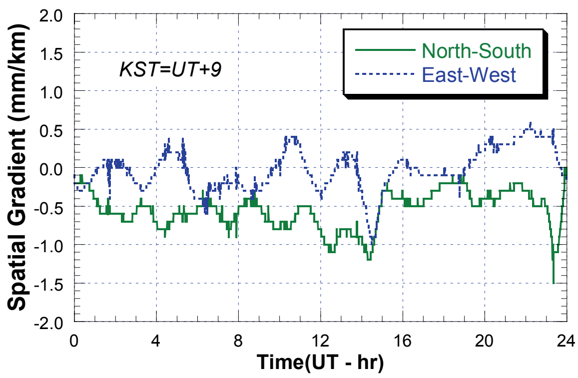

Figure 4 Ionosphere delay gradient variation in 2003.11.20 (grid map differentiation – smoothed code)

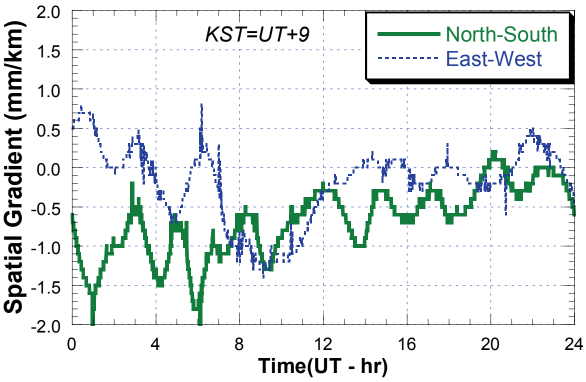

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Figure 5 Ionosphere delay gradient variation in 2003.10.27 (grid map differentiation – smoothed code)

As mentioned before, two types of ionospheric spatial gradient were computed using (1) grid based map and (2) direct measurement differentiation. Figures 3, 4 and 5 show the ionospheric gradient along the north-south and east-west directions. Figure 3 uses code measurements only while Figure 4 uses the grid map data using carrier smoothed code measurements. Reduction of the small fluctuation is significant for the smoothed results while the overall trend is retained. The figures for November 20 show certain increase around UT 12 when the storm became effective. The large increase near the end of day is partly due to the data arc length, i.e. the data was processed as daily basis. In overall, the north-south gradient is higher than the east-west gradient. It is because the ionosphere distribution is mainly dependent of latitude and Korea is just above the equatorial anomaly region, where large ionospheric delay is present with high activity. This result implies that an aircraft approaching along a north-south runway is more affective to the storm than an aircraft along an east-west runway. The cause of the fluctuation in the both direction is not clearly identified yet.

Figures 6 and 7 show the ionospheric spatial gradient using the direct differentiation method. The average of the gradient values along the two directions is computed at each epoch. As like the map based method, the storm day gradient (November 20) shows some gradient increase during the local night time, around UT12~14. The quiet time gradient (October 27) shows higher gradient and no significant increase during the local night time. Both figures show that the north-south gradient is larger than the east-south one. The spikes represent abnormal gradient increase. It is not clear that the cause of the sudden increase is whether actual gradient increase or measurement noise. At this moment, isolation methodology of the noise from the storm signal is not fully developed yet.

Another storm day of October 29, 2003 was also analyzed to compare with the quiet day of October 27. Since there is three weeks gap between the November 20 and October 27, it is better to use the closer day data. In addition to the ionospheric gradient time-series, the gradient statistics is compared. Unlike Figures 3 through 7, the measured gradients are not classified into the north-south and east-west directions. Instead the measured gradients are binned to figure out the gradient distribution. Figure 8 compares the ionospheric gradient distribution in two storm days and one quiet day. Comparison of October 29 data with October 27 data shows some increase of high gradient (slope) value.

On the other hand, November 20 data shows even less percentage of high gradient when compared with October 27 data. Since the ionosphere delay level is decreased during winter,

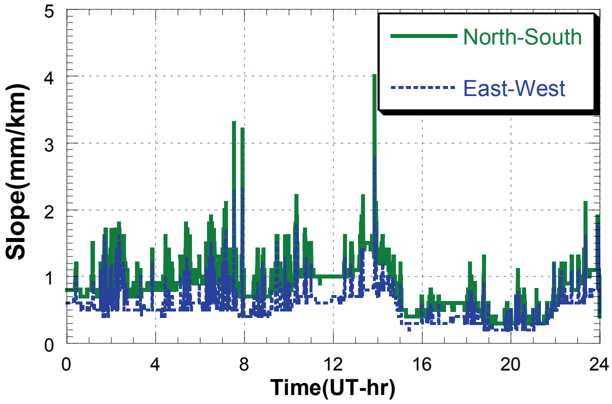

Figure 6 Ionosphere delay gradient variation in 2003.11.20 (measurement differentiation – smoothed code)

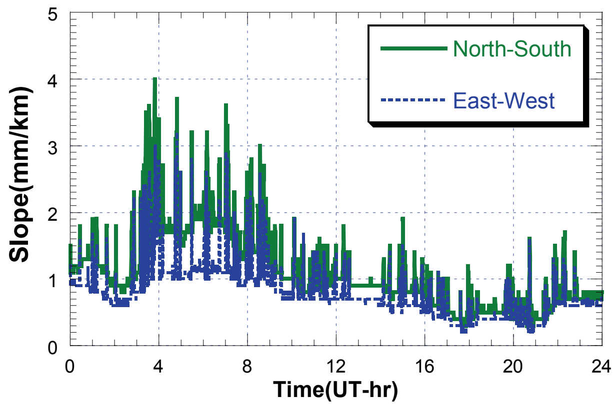

Figure 7 Ionosphere delay gradient variation in 2003.10.27 (measurement differentiation – smoothed code)

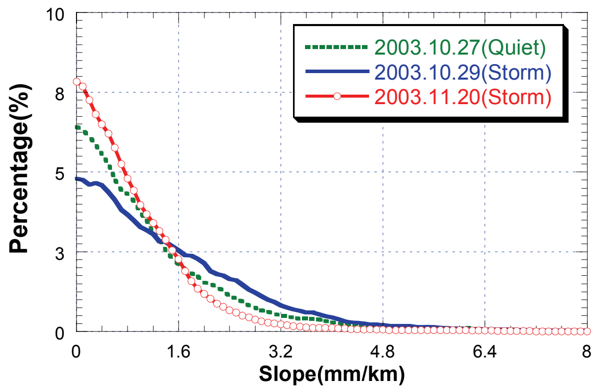

Figure 8 Ionosphere delay gradient statistics

the gradient level is also decreased during winter.

Due to this seasonal variation, October 27 data shows even higher gradient than November 20 data. Other than the comparison, the gradient level is usually less than 5mm/km and the mean value is about 2mm/km. However this result is limited to 2003 data and autumn (October-November) data. The ionospheric gradient may be quiet different from the high solar activity period, e.g. 2001, and quiet period, e.g. 2006. Extensive data analysis is necessary to identify the gradient variation pattern as a function of solar activity, seasonal or diurnal variations.

4. Conclusion

In order to apply to GNSS augmentation systems, preliminary analysis on the ionospheric spatial gradient was performed. A code for computing the ionospheric gradient has been developed and preliminary results are presented. Since the ionosphere behavior shows different patterns with different location, analysis on the effect of the ionosphere storm and ionospheric gradient characteristics should include regional characteristics.

GPS observation data over Korean peninsular for recent storm days (November 20, 2003) were processed for generating ionosphere maps and ionospheric gradients. Abrupt ionospheric delay changes and gradient increase are identified while they are not significant as much as Europe and North America during the same period. However, the observation data is limited for specific period and the gradient computation program needs many enhancements.

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