Ionospheric Storm Detection Method Using Multiple GNSS Reference Stations

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ABSTRACT

In this work, we propose detection method for ionosphere storm that occurs locally using widespread GNSS reference stations. For ionosphere storm detection, we compare ionosphere condition with other reference stations and estimate direction of movement based on ionosphere time variation. The method use carrier phase measurement of dual frequency, for accuracy and precision of test statistics, are evaluated with multiple GNSS reference stations data.

Keywords: GNSS multiple reference stations, ionospheric storm detection, dual-frequency carrier phase

1. INTRODUCTION

In terms of GNSS augmentation systems, ionospheric storms began to draw attention after it was observed by WAAS reference stations (baseline length 40 ~ 100 km) distributed throughout the US at 20:15 UTC in November, 2003. The observed ionospheric storm had a slope of about 425 mm/km (Datta-Barua et al. 2008). Ionospheric storms are a threat to GNSS augmentation systems because it is difficult to predict when and where they will occur and how strong they will be. If the ground station of the augmentation system differs from the user's ionosphere environment, errors occur in the correction information from the reference station, thus leading to increased user position errors (Hoffmann-Wellenhof et al. 2008). Therefore, based on previous cases, the US parameterized ionospheric storm

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Jongsun Ahn https://orcid.org/0000-0002-5432-4436 Sangwoo Lee https://orcid.org/0000-0002-0642-5064 Moonbeom Heo https://orcid.org/0000-0001-9674-9937 Eunseong Son https://orcid.org/0000-0002-0701-9965 Young Jae Lee https://orcid.org/0000-0002-9203-048X models for worst-case scenarios where ionospheric storms could affect GNSS local augmentation systems (Datta-Barua et al. 2010). We also estimated the maximum ionospheric storm slope observed in Korea based on data from multiple reference stations (2000 ~ 2004) distributed throughout the country (Kim et al. 2014).

Two types of methods have been proposed to detect ionospheric storms: a method that uses measurements that show different characteristics when GNSS system signals pass through the ionosphere, and a method that monitors the influence of the ionospheric storm on the user position error. In terms of measurements, the typical detection method is Code-Carrier Divergence (CCD). The code and carrier measurements of the GNSS system are subject to different effects as they pass through the ionosphere, in which the code experiences a delay while the carrier experiences an advance. If the thickness of the ionosphere increases dramatically due to ionospheric storms, the difference between the two measurements gradually increases to the extent of divergence (Cho et. al 2015). Using this, the CCD method detects ionospheric storms based on the Geometric Moving Average filter with the time variation of the code and carrier difference values (Simili & Pervan 2006). However, as CCD is a detection method using code measurements, the precision of the test statistics may be low because of the noise included in the measurements, especially in the case of low elevation satellites. Moreover, considering the characteristics of local and moving ionospheric storms, when operating only in a single reference station, the detection time may be delayed. Therefore, a method was proposed to double-difference precise carrier phase measurements between multiple reference stations rather than code measurements, and use baseline information (Khanafseh et al. 2012). However, this method is also based on the assumption that the line-of-sight vectors between specific satellites produced in multiple reference stations are parallel, and thus has limitations in the detection range due to the limit of baseline length between multiple reference stations. In order to upgrade the accuracy and precision of test statistics and improve narrow detection range limits, this study proposed a method to compare the variation of ionospheric thickness of individual reference stations by using dual-frequency carrier and further estimate the direction of ionospheric storms.

2. MAIN TOPICS

2.1 Detection Method Configuration

First, calculate the variation of the ionospheric vertical delay over the individual reference stations based on the same satellites received from multiple reference stations through Dual Frequency Carrier Divergence (DFCD) based on dual-frequency carriers. Then, compare the variations among multiple reference stations and calculate the similarity of ionospheric storm thickness variation through the I-Value to detect ionospheric storms that occur over a specific reference station. Lastly, derive the inverse weights of the visible satellites based on the I-Value and estimate the direction of the ionospheric storm by applying the difference of DFCD between the reference stations to the least-squares method (Ahn 2015).

2.2 DFCD Inspection

DFCD refers to the time variation of geometry-free values of different frequency carrier measurements. This study developed an equation for geometry-free measurements based on the carrier measurement (Φ) of L1 and L2.

$$\Phi_{1} = \frac{1}{\lambda_{1}}R + \frac{c}{\lambda_{1}}\Delta\delta + N_{1} - \frac{1}{\lambda_{1}}I_{1} = \frac{f_{1}}{c}R + f_{1}\Delta\delta + N_{1} - \frac{f_{1}}{c}I_{1}$$
(1)

$$\Phi_{2} = \frac{1}{\lambda_{2}}R + \frac{c}{\lambda_{2}}\Delta\delta + N_{2} - \frac{1}{\lambda_{2}}I_{2} = \frac{f_{2}}{c}R + f_{2}\Delta\delta + N_{2} - \frac{f_{2}}{c}I_{2}$$
(2)

R: Actual distance (satellite-user antenna, m), $\Delta \delta$: Satellite clock error (sec) *c*: Speed of light (m/s), *f*₁, *f*₂: *L*1, *L*2 carrier frequency, *I*₁, *I*₂: *L*1, *L*2 ionospheric delay (m) λ_1, λ_2 : Length of 1 wavelength of *L*1, *L*2 frequency carrier, *N_n*: *n* frequency carrier integer ambiguity

Multiplying the L1 carrier measurement by the L2 frequency value, and the L2 carrier measurement by the L1 frequency value, respectively, yields Eqs. (3) and (4), which can be converted to geometry-free measurements that can offset the effect of the actual distance and the satellite clock error.

$$f_2 \Phi_1 = f_1 \frac{f_2}{c} R + f_1 f_2 \Delta \delta + f_2 N_1 - f_2 \frac{f_1}{c} I_1$$
(3)

$$f_1 \Phi_2 = f_1 \frac{f_2}{c} R + f_1 f_2 \Delta \delta + f_1 N_2 - f_1 \frac{f_2}{c} I_2$$
(4)

As shown in Eq. (5), if Eq. (3) is differenced by Eq. (4) and then divided by the L2 carrier frequency, only the effects of the integer ambiguity in each carrier and the ionospheric delay error will remain.

$$\Phi_{12} = \Phi_1 - \frac{f_1}{f_2} \Phi_2 = N_1 - \frac{f_1}{f_2} N_2 - \frac{1}{c} \left(1 - \frac{f_1^2}{f_2^2} \right) \frac{40.3}{f_1} F_{pp} VTEC$$
$$= N_1 - \frac{f_1}{f_2} N_2 - b \frac{40.3}{f_1} F_{pp} VTEC$$
(5)

$$I_{k} = \frac{40.3}{f_{k}^{2}} VTEC, VTEC: Vertical Total Electron Content$$
$$F_{pp} = \left[1 - \left(\frac{R_{e} \cos \theta^{i}}{R_{e} + h_{I}}\right)^{2}\right]^{\frac{1}{2}}$$

 θ^i : Elevation angle of satellite i at observing site (deg.) θ^i : Zenith angles at the ionospheric point (deg.) h_i : 350 km (Mean value for the height of the ionosphere) R_e : 6378.1363 km (Mean radius of the earth) dt: Sample interval

In order to offset the effect of the integer ambiguity, timedifferencing Eq. (5) and assuming that the variation of the obliquity factor over time is minimal will yield Eq. (6). At this point, we assume that the integer ambiguity of each carrier is the same. This allows us to monitor the variation of the ionosphere over time by excluding the constants included.

$$\Phi_{12}(t) - \Phi_{12}(t-1) = -\frac{1}{f_1} \left(1 - \frac{f_1^2}{f_2^2} \right) \frac{40.3}{c} F_{pp}(t) \Delta VTEC(t)$$
 (6)

Because the satellite elevation angle of the same satellite is different for each reference station, the influence of the



Fig. 1. CCD and DFCD test statistics of normal condition.



Fig. 2. CCD and DFCD histogram of normal condition.

ionosphere in the slant direction between the satellite and the reference station antenna may be different. In order to compare them from the same perspective, converting and organizing the slant direction values to vertical directions will yield Eq. (7).

$$DFCD(t) = \frac{\Phi_{12}(t) - \Phi_{12}(t-1)}{b \times f_1 \times F_{pp} \times dt} = -\frac{40.3}{f_1} \frac{VTEC}{dt} = I_{vert}^{DFC}$$
(7)
$$b = \frac{1}{c} \left(1 - \frac{f_1^2}{f_2^2}\right)$$

This paper defined Eq. (7) as the DFCD value and used it as a test statistic to monitor the time variation of the ionosphere thickness. To compare the degree of precision of the DFCD test statistic, we compared the CCD based on the code measurements with the same physical meaning and the test statistics under normal conditions, as shown in Figs. 1 and 2.

Fig. 2 is a histogram to derive the standard deviation of the test statistics, in which the X-axis represents the size of the test statistic and the Y-axis represents the number of samples. We can confirm the DFCD is a more precise test statistic value as the standard deviation (1σ) of DFCD is 0.001 m/s compared to that of CCD (0.058 m/s). The precision of the test statistic can be configured as the precise threshold





Fig. 3. Ionospheric vertical divergence with respect to elevation angle.

value to determine failure, thereby improving failure detection performance. Fig. 3 shows the ionospheric vertical delay according to the satellite elevation angle by using long-term data. It can be seen that there is a 5 to 25 times precision difference between DFCD and CCD.

Through statistically analyzing the test statistics according to the satellite elevation angle, the threshold value required for failure detection can be expressed as an exponential function as shown in Eq. (8) and Table 1.



Fig. 4. Test result on simulated ionospheric storm condition.

Table 1. Exponential function model of ionospheric delay variation (m/s).

Detection method	а	b	с	d
CCD	0.004461	-0.07924	0.00411	-0.00159
DFCD	-0.000151	-0.07612	0.00177	-0.02435

 $\sigma^{i}(\theta) = a e^{(b+\theta)} + c e^{(d+\theta)}, \theta: \text{ Satellite elevation angle (in deg.)}$ (8)

In addition, as a result of examining the accuracy of the test statistics in detecting the variation of ionospheric thickness by inserting a constant ionospheric vertical delay (0.2 m/s) and the vertical delay of a constant acceleration (0.005 m/s^2) into the same satellites (5 satellites) as shown in Fig. 4, the DFCD value was found to be also superior to the CCD value in terms of accuracy.

2.3 I-Value Inspection

The satellites that have passed the DFCD inspection, which is an ionospheric vertical delay variation test, are checked for similarities with the DFCD values of the common satellites with neighboring reference stations. This method is to monitor ionospheric storms with local error characteristics. If the I-Value of a specific satellite or a reference station in a specific region increases, we can suspect an ionospheric storm in that region. This can be expressed as Eq. (9).

$$IV_{j}^{i} = \frac{1}{M} \sum_{n=1}^{m} DFCD_{n}^{i} - \frac{1}{M-1} \sum_{\substack{n=1\\n\neq j}}^{m-1} DFCD_{n}^{i}$$
(9)



Fig. 5. Conceptual diagram of ionospheric storm condition on multiple reference stations.

M: Number of multiple reference stations, *j*: Reference station index, *i*: Satellite index

The first term on the right side of Eq. (9) represents the mean DFCD value for the same satellite of M reference stations and the second term represents the mean DFCD value calculated for the rest of the reference stations except for the reference station in a specific region. By differencing this, we can calculate the I-Value of receiver *j*, which was excluded from the last term for satellite *i*. This is illustrated in Fig. 5. Assuming that the ionospheric storm is affecting satellite *i* received at reference station 1, the mean DFCD value of the entire reference stations for satellite I is increased by the DFCD value of reference station 1. At this point, in terms of differencing by the mean DFCD value of the reference stations other than reference station 1, they converge close to '0' under normal conditions because the DFCD values are similar between the reference stations, but when an ionospheric storm occurs, the I-Value increases.



Fig. 6. I-Value variation with respect to elevation angle.

Table 2. Exponential function model of I-value (m/s).

Detection method	а	b	С	d
CCD	0.00059	-0.03464	0.001243	-0.0041
DFCD	-4.968e-005	-0.05884	2.423e-005	0.001943

This indicates that the thickness of the ionosphere in the direction of satellite i is rapidly changing over reference station 1.

As in the case of DFCD, the standard deviation of the sample increases due to reduced noise as the elevation angle increases. Fig. 6 shows the results of analyzing this according to the satellite elevation angle.

As seen from the results in Fig. 6, it can be confirmed that the I-Value produced based on the DFCD value shows higher precision throughout the satellite elevation angle section compared to the I-Value based on CCD. Modeling this in the form of an exponential function is shown in Eq. (10) and Table 2.

 $\sigma_{W}^{i}(\theta) = a e^{(b+\theta)} + c e^{(d+\theta)}, \ \theta: \text{ satellite elevation angle (deg.)}$ (10)

2.4 Estimating the Direction of the lonospheric Storm Based on the De-weighted Least-squares Method

As the final step of detecting ionospheric storms, this study estimates the direction of the storm in relation to reference stations where the difference of DFCD values is relatively large through the I-Value. This allows the operator of the reference station to alert the areas that may be affected in advance based on the information of the ionospheric storm progressing in a particular direction.

Based on reference station A to detect the direction of the ionospheric storm, we can calculate the ionospheric delay relative to reference station B, as shown in Eq. (11). Project this into the location area to calculate the error due to the difference in the ionospheric delay error and estimate the direction of the ionospheric storm based on the direction of the error.

$$\Delta I_{AB}^{i} = \left(DFCD_{B}^{i} - DFCD_{A}^{i} \right) \times \Delta t$$

$$\Delta t; \text{ Sampling time (sec)}$$
(11)

The observation matrix to project into the location area is produced as shown in Eq. (12) by configuring a line-ofsight vector based on the reference station coordinates, the satellite coordinates calculated from the satellite navigation messages, and the actual distance. The position error is calculated by the least-squares method, as shown in Eq. (13). Eventually, the value derived from Eq. (13) is the error in Earth-centered Earth-fixed (ECEF) coordinate system caused by the difference in the ionospheric delay error between two reference stations (A, B). By converting this into the Topocentric (ENU, East North Up) coordinate system, we can estimate the direction of the ionospheric

storm based on reference station (A).

$$\begin{bmatrix} \Delta I_{AB}^{1} \\ \Delta I_{AB}^{1} \\ \vdots \\ \Delta I_{AB}^{1} \\ \vdots \\ \Delta I_{AB}^{i} \end{bmatrix} = \begin{bmatrix} -\frac{x^{1} - x_{A}}{\rho_{A}^{i}} & -\frac{y^{1} - y_{A}}{\rho_{A}^{i}} & -\frac{z^{1} - z_{A}}{\rho_{A}^{i}} \\ -\frac{x^{2} - x_{A}}{\rho_{A}^{i}} & -\frac{y^{2} - y_{A}}{\rho_{A}^{i}} & -\frac{z^{2} - z_{A}}{\rho_{A}^{i}} \\ \vdots & \vdots & \vdots \\ -\frac{x^{i} - x_{A}}{\rho_{A}^{i}} & -\frac{y^{i} - y_{A}}{\rho_{A}^{i}} & -\frac{z^{i} - z_{A}}{\rho_{A}^{i}} \end{bmatrix} \begin{bmatrix} \Delta x_{A} \\ \Delta y_{A} \\ \Delta z_{A} \end{bmatrix} + \varepsilon \quad (12)$$

$$\rho_{A}^{i} = \sqrt{(x^{i} - x_{A})^{2} + (y^{i} - y_{A})^{2} + (z^{i} - z_{A})^{2}}$$
: Geometry truerange (m)

 $\Delta \hat{\mathbf{x}}_{A} = \begin{bmatrix} \Delta x_{A} & \Delta y_{A} & \Delta z_{A} \end{bmatrix}^{T}$: Position error (ECEF, XYZ) x_{A}, y_{A}, z_{A} ; Reference coordinate (ECEF, m)

$$\Delta \hat{\mathbf{x}}_{A} = \left(\mathbf{H}^{T}\mathbf{H}\right)^{-1}\mathbf{H}^{T}\Delta \mathbf{I}_{AB}$$
(13)

2.4.1 De-weighting-based least-squares method

In general, the measurements applied to the leastsquares method do not all have the same error. Therefore, we use the weighted least-squares method as shown in Eq. (14) by assigning different weights for each measurement and higher weights to satellites with relatively low errors.

$$\Delta \hat{\mathbf{x}}_{u} = \left(\mathbf{H}^{T} \mathbf{W} \mathbf{H}\right)^{-1} \mathbf{H}^{T} \mathbf{W} \Delta \boldsymbol{\rho}$$
(14)

$$\mathbf{W}^{-1} = \begin{bmatrix} \sigma^{1,2} & 0 & \cdots & 0 \\ 0 & \sigma^{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma^{i,2} \end{bmatrix}$$
(15)

However, in this study, we can increase the effect of estimating the direction by increasing the weights on the

Table 3.	GBAS airborne accuracy designator.
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AAD	a ₀ , AAD	$a_{\nu}AAD$	θ_{C}, AAD
AAD-B	0.11	0.13	4.0

Table 4. GBAS ground accuracy designator.

	GAD	a ₀ , GAD	a_{ν} GAD	a ₂ , GAD	$\theta_{O} GAD$
GAD-C	θ >=35	0.15	0.84	0.04	15.5
	θ^{i} <35	0.24	0	0.04	-

measurements in the directions of potential ionospheric storms, instead of applying the reciprocal of the standard deviation of the measurement error as the weight.

$$\mathbf{W}_{d} = \begin{bmatrix} w_{d}^{1} & 0 & \cdots & 0 \\ 0 & w_{d}^{2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & & w_{d}^{i} \end{bmatrix}$$
(16)

$$w_{d}^{i} = \frac{1}{\sigma^{i,2}} + \sigma^{i,2}_{iono,n}$$
(17)

 σ^i : Error standard deviation model under normal conditions (m) σ^i_{iono} : Relative ionospheric vertical delay error standard deviation between network reference stations (m)

Eqs. (16) and (17) show the type of weights used in this paper, which basically reduce the weights due to error factors under normal conditions as in the case of conventional methods, but increase the weights of satellite measurements that are suspected of ionospheric storms. The error model under normal conditions and the related constants are shown in Eq. (18), and Tables 3 and 4 (U.S. Federal Aviation Administration 2005). Based on Eq. (18), the size of the detailed factors constituting the error under normal conditions according to the elevation angle is as shown in Fig. 7.

$$\sigma^{i} = \sqrt{\sigma_{multipath}^{i,2} + \sigma_{noise}^{i,2} + \sigma_{pr_{gnd}}^{i,2}}$$
(18)

 $\sigma_{multipath}^{i} = 0.13 + 0.53e^{-\theta_{10}^{i}}$: Multi-path error model

 $\sigma_{noise}^{i} = a_{0,AAD} + a_{1,AAD} e^{-\theta_{c,AAD}^{i}}$: User signal noise error model

 $\sigma_{pr_{gnd}}^{i} = \sqrt{\frac{\left(a_{0,GAD} + a_{1,GAD}e^{-\theta^{i}/\theta_{0,GAD}}\right)^{2}}{M} + \left(a_{2,GAD}\right)^{2}} : \text{Reference station}$ error model

θ: Satellite elevation angle (Deg.), *M*: Ground reference stations (4 locations)

The de-weighted error model applies the standard deviation of the DFCD or CCD values generated by the



Fig. 7. Measurement error model of normal condition.

reference station. At this point, the standard deviation value after the normalization process is used as the sample to calculate the standard deviation.

$$CCD_{m,n}^{i} = \frac{\mu_{CCD}^{i} - CCD_{m}^{i}}{\sigma_{CCD}^{i}}$$
(19)

$$DFCD_{m,n}^{i} = \frac{\mu_{DFCD}^{i} - DFCD_{m}^{i}}{\sigma_{DFCD}^{i}}$$
(20)

The mean and standard deviation used in the normalization process were statistics under normal conditions; the mean was '0' and the standard deviation was the model value based on Eq. (8) and Table 1. There is no problem in the normalization process under normal conditions, but in the event of an ionospheric storm, performing the normalization process with the values above is not appropriate from a statistical perspective. However, in terms of performing the normalization process with the values above from a failure detection perspective, we can easily derive values that are not normalized (mean '0' standard deviation '1'). Calculating the standard deviation of the DFCD and CCD values of each reference station after performing normalization is as shown in Eq. (21).

$$\sigma_{iono,DFCD}^{i} = \sqrt{\frac{\sum_{m=1}^{M} \left(DFCD_{m}^{i} \right)^{2}}{M-1}}, \ \sigma_{iono,CCD}^{i} = \sqrt{\frac{\sum_{m=1}^{M} \left(CCD_{m}^{i} \right)^{2}}{M-1}} \quad (21)$$

2.4.2 Theoretical characteristics of the de-weighting-based least-squares method

This section will discuss the theoretical characteristics of the de-weighted least-squares method by numerically analyzing the unbiasedness and increase of variance. First, the configuration of the least-squares method to determine the theoretical Unbiasedness of the de-weighted leastsquares method is as shown in Eqs. (22) and (23).



$$\Delta \mathbf{I} = \mathbf{H} \Delta \mathbf{X} + \boldsymbol{\varepsilon} \tag{22}$$

$$\Delta \hat{\mathbf{X}} = \left(\mathbf{H}^T \mathbf{W}_d \mathbf{H}\right)^{-1} \mathbf{H}^T \mathbf{W}_d \Delta \mathbf{I}$$
(23)

Substituting Eq. (23) into Eq. (22) leads to Eq. (24), and taking the expected value on both sides yields Eq. (25).

$$\Delta \hat{\mathbf{X}} = \underbrace{\left(\mathbf{H}^{T}\mathbf{W}_{d}\mathbf{H}\right)^{-1}\mathbf{H}^{T}\mathbf{W}_{d}\mathbf{H}}_{I}\mathbf{X} + \left(\mathbf{H}^{T}\mathbf{W}_{d}\mathbf{H}\right)^{-1}\mathbf{H}^{T}\mathbf{W}_{d}\boldsymbol{\varepsilon}$$
$$= \Delta \mathbf{X} + \left(\mathbf{H}^{T}\mathbf{W}_{d}\mathbf{H}\right)^{-1}\mathbf{H}^{T}\mathbf{W}_{d}\boldsymbol{\varepsilon}$$
(24)

$$E\left[\Delta \hat{\mathbf{X}}\right] = \Delta \mathbf{X} + \left(\mathbf{H}^{T} \mathbf{W} \mathbf{H}\right)^{-1} \mathbf{H}^{T} \mathbf{W} \underbrace{E\left[\boldsymbol{\varepsilon}\right]}_{0}$$
(25)

The noise component (ϵ) follows a Gaussian distribution, which results in the characteristics as shown in Eq. (26) if assuming that each error component is independent. By reflecting this, we can consider the expected value of the solution as estimated in Eq. (27) to be equal to the actual value. This shows that the least-squares method is unbiased even in the case of using the de-weighted weights.

$$E\left[\varepsilon^{i}\right] = 0, \ Var\left[\varepsilon^{i}\right] = \sigma^{i,2}$$
(26)

$$E\left[\Delta \hat{\mathbf{X}}\right] - \Delta \mathbf{X} = 0 \tag{27}$$

The estimation error variance of the conventional weighted least-squares method is as shown in Eq. (28), which helps to examine the characteristics of the variance.

$$Var\left[\Delta \hat{\mathbf{X}}\right] = Var\left[\left(\mathbf{H}^{T}\mathbf{W}\mathbf{H}\right)^{-1}\mathbf{H}^{T}\mathbf{W}\Delta\mathbf{y}\right]$$
(28)

Eq. (29) expresses this in the form of expected values.

$$E[\Delta \mathbf{x} \Delta \mathbf{x}] = (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1} \mathbf{H}^{T} \mathbf{W} E[\Delta \mathbf{y} \Delta \mathbf{y}] \mathbf{W}^{T} \mathbf{H} (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1}$$
$$= (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1} \mathbf{H}^{T} \underbrace{\mathbf{W} \mathbf{W}^{-1}}_{I} \mathbf{W}^{T} \mathbf{H} (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1}$$
$$= (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1} \underbrace{\mathbf{H}^{T} \underbrace{\mathbf{W}^{T} \mathbf{W}}_{I} \mathbf{W} \mathbf{H} (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1}}_{I}$$
$$= (\mathbf{H}^{T} \mathbf{W} \mathbf{H})^{-1} \tag{29}$$

If comparing the variances of the conventional weighted least-squares method and the de-weighted least-squares method using Cauchy-Schwarz inequality as shown in Eq. (30), the size of the variance is determined according to the size of the weight.

$$\mathbf{H}^{T}\mathbf{W}\mathbf{H} \leq \left\|\mathbf{H}^{T}\right\| \left\|\mathbf{W}\right\| \left\|\mathbf{H}\right\| \tag{30}$$

By comparing the size of the weights using Eq. (31), it can be seen that the variance of the de-weighted least-squares method is larger than that of the conventional weighted least-squares method, as shown in Eq. (32). Therefore, the de-weighted least-squares method is effective in terms of integrity rather than accuracy because it reacts sensitively to local ionospheric storms.

$$\frac{1}{\underline{\sigma}^{i,2}} + \sigma^{i,2}_{iono} \ge \frac{1}{\underline{\sigma}^{i,2}}$$
(31)

$$Var\left[\hat{\mathbf{X}}_{W}\right] \leq Var\left[\mathbf{X}_{DW}\right]$$
(32)

Based on Eqs. (31) and (32), Fig. 8 shows how the weight changes when there is a difference in the variation of



Fig. 9. Simulation geometry condition of reference station and visible satellites.



Fig. 10. Estimation results of simulated ionospheric storm direction.

Table 5. Simulation data.

Receiver	Date	Time interval	Total time
Trimble NETR5 or NetR9	2015.04.01	30 s	24 h

ionospheric vertical delay. In reality, changes in weight occur when there is a change in visible satellites over time; thus, we assumed PRN 7, 16, 19, and 27 at any random time during the analysis period. If inserting a 0.001 m/s² failure in a specific reference station, PRN No. 16, after 12 o'clock, the weight would be calculated to be low by the conventional method because the elevation angle of satellite No. 16 is low, but the weight increases through the de-weighting process.

2.4.3 lonospheric storm direction estimation simulation results

As shown in Fig. 9, this study used GNSS reference stations in 5 locations (Cheonan, Sejong, Boeun, Goesan, Cheongju) for simulation. The simulation was performed under the assumption that PRN No. 2 and PRN No. 20 received at Boeun reference station were influenced by an ionospheric storm (ionospheric vertical delay variation: 0.001 m/s2), individually or at the same time. The failure was selected to be of a size that can cause performance difference compared to CCD, which is currently used as the reference group. In addition, although the total data reception time was 24 hours as shown in Table 5, this study examined the results for 20 epoch (600 s) in order to review the changes in I-Values and weights in the same satellite group.

Under the assumption that the ionospheric storm may affect a single satellite or multiple adjacent satellites, we estimated the directions according to two scenarios. Fig. 10 shows the estimation results according to these scenarios. As shown in Fig. 10, the CCD-based estimation method cannot estimate the direction of the ionospheric storm due to intrinsic noise. On the other hand, the DFCD method precisely maintains a position error close to '0', and moves in the direction of PRN No. 2 at the moment a failure occurs, indicating an increase in error. Similarly, in the case of multiple satellites, the direction of the position solution error indicates between PRN No. 2 and PRN No. 20.

3. CONCLUSTION

This paper proposed a method to detect ionospheric storms based on multiple reference stations. The detection method is divided into 3 steps, which start with examining the variation of ionosphere vertical thickness over individual reference stations and the I-Value which monitors the similarity of the variations, and end with presenting a method to monitor the direction. First, the variation of ionospheric vertical delay was examined to detect ionospheric storms from individual reference stations. The variation of ionospheric vertical delay based on DFCD was estimated based on carriers and was found to be superior to code in terms of the degree of precision. After extending this to networked reference stations, this study introduced the concept of I-Value, a value that monitors the consistency of DFCD values transmitted from the individual reference stations-the similarity of ionospheric states over the networked reference stations. I-Value is the same concept as the B-Value currently used to detect receiver failures in GBAS. As an example of operation, if the I-Value from a specific reference station diverges by comparing the DFCD values of each reference station from the same single satellite, we can detect the unstable state of the ionosphere over the corresponding area.

The detection results based on I-Value can be used to estimate the approximate direction of the ionosphere, but this study applied the de-weighted least-squares method to estimate a more accurate direction. The weighted least-squares method is a typical method to estimate the navigation solution in satellite navigation systems. The least-squares method estimates the navigation solution by finding the point at which the sum of the squared residuals of the measurements and estimates of the distance of each satellite is minimized. If there is an error in the measurement of the distance of a specific satellite, a navigation solution error occurs in the opposite direction of the specific satellite unless there are satellites in other directions to offset the error. This is applied to estimate the direction of the ionospheric storm. If any given satellite is within the influence of the ionospheric storm, the measurement delay error will increase, and we can find out which satellites are within the influence of the ionospheric storm by applying this to the least-squares method to calculate the residual solution. In general, the weights used in the least-squares method reduces the navigation solution error by reducing the weights of the satellites with

high errors. However, this study applied "de-weighted" weights to increase the weights of the satellites assumed to be influenced by the ionosphere, thereby increasing the sensitivity of the ionospheric storm direction rather than the accuracy of the navigation solution. Here, the weights are generated based on the I-Value mentioned above. This method can be applied to GNSS augmentation application systems to detect ionospheric storms in conjunction with reference stations currently operating in Korea.

AUTHOR CONTRIBUTIONS

Conceptualization, J. Ahn and Y. J. Lee; methodology, J. Ahn; software, J. Ahn, and E. Son; validation, J. Ahn, Y. J. Lee; formal analysis, S. Lee and E. Son; investigation, J. Ahn and Y. J. Lee; writing—original draft preparation, J. Ahn and Y. J. Lee; writing—review and editing, S. Lee, M. Heo and E. Son

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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