A Vector Ionospheric Delay Correction Method for GNSS Positioning and Navigation Wide Area Augmentation Service

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Abstract. A new ionospheric delay correction method is proposed to improve the ionospheric correction accuracy of single frequency GNSS users. In the new method, the ionospheric grid point information is expanded from a single scalar vertical correction parameter to a vector of triple elements (the triple): vertical correction parameter, north correction parameter and east correction parameter. The new parameters are used to describe the variation of ionospheric delay correction caused by satellite azimuth. Using the observation data of the ground monitoring stations to fit the triple, and then broadcast the triple to the user. GNSS single frequency users can use the triple data to correct their own ionospheric delay. The testing results show that the correction error of the method is around 0.3 m lower than that of the scalar method.

Keyword: GNSS, GPS, Ionosphere, TEC, Navigation augmentation.

1. Introduction
Ionospheric delay is the largest positioning error source for GNSS single frequency users. In order to improve the positioning accuracy of single frequency users, the ionospheric delay must be corrected by augmentation system. For example, for the widely used satellite-based augmentation system (SBAS), it is assumed that all free electrons in the atmosphere are concentrated on a thin spherical shell with an altitude of 350 km [1]. The global ionosphere is divided into 1320 grid points according to longitude and latitude. The augmentation system estimates the vertical ionospheric delay of these grids through the ground-based monitoring station, and then broadcasts the data in SBAS message through GEO satellite, single frequency receivers can use the grids information for ionospheric correction.

One of the important problems in the above ionospheric delay correction methods is that the distribution of electron density along the altitude direction is ignored. As shown in figure 1, for two observations passing the same ionospheric puncture point (IPP) at the same time, if one observation’s satellite is in the north, the receiver is in the south, the other’s satellite is in the south, and the receiver is in the north, as long as the zenith angles of the two observations are the same, the ionospheric correction amount obtained from the existing scalar grid information is the same, that is to say, the ionospheric correction is related to the position of the IPP and zenith angle only, but not to the azimuth of the observation.
However, due to the large contribution of free electrons of the plasma layer, the electron density distribution on the ionospheric shell is not isotropic. The research of Prof. Belehaki shows that the plasma layer can contribute more than 50% total electron content (TEC) in extreme cases at night and 20% at normal night [2]. The TEC delays of the two observations in figure 1 may be quite different, especially at sunrise/sunset, at night in winter and spring, or when ionospheric disturbances occur. Then the ionospheric correction error will increase and the positioning accuracy will decrease.

In order to solve the above problem, a vector ionospheric delay correction method is introduced in this paper. The specific contents and experimental results are described in detail in the following chapters.

2. Algorithms
The core content of vector ionospheric correction is to upgrade the ionospheric grid point correction parameter $d\tau$ from a single scalar to an array vector. The first-order vector ionospheric correction parameter contains three elements as shown in equation (1):

$$d\tau = [d\tau_0, d\tau_{n1}, d\tau_{e2}]$$

where $d\tau_0$ is the 0-order ionospheric correction parameter, which is equivalent to the grid ionospheric correction scalar $d\tau$ for downward compatibility. $d\tau_{n1}$ is the ionospheric correction northward gradient and $d\tau_{e2}$ is the ionospheric correction eastward gradient.

The specific implementation steps are as follows: 1. Monitoring network measures the ionospheric delays; 2. Central processing server collects the ionospheric delay measurement data; 3. Central processing server converts the ionospheric delay data into vector ionospheric products; 4. Vector ionospheric products are broadcasted through network, radio or satellite; 5. The user uses the vector ionospheric products to correct the ionospheric delay.

2.1. GNSS Data Preprocessing
There are a lot of researches about GNSS dual frequency observation data processing [3,4]. In this paper, taking GPS as an example, a brief description is given below. The basic formula of TEC calculation using GPS dual frequency phase observation data is shown in equation (2) and (3):

$$\text{STEC} = n_0(L_1\lambda_1 - L_2\lambda_2 + l_1\lambda_1 - l_2\lambda_2) - B_s - B_v$$

$$n_0 = \frac{8\pi^2\varepsilon_0 m(f_1 f_2)^2}{e^2(f_1^2 - f_2^2)} = 9.517 \times 10^{16} \text{ m}^{-3}$$

where $f_1=1.57542 \text{ GHz}$, $f_2=1.22760 \text{ GHz}$ are the dual frequencies of the carriers of GPS system; $\lambda_1$ and $\lambda_2$ are the wavelengths of these two carriers; $l_1$ and $l_2$ are phase observations; $L_1$ and $L_2$ represent the
integer ambiguity of the corresponding carrier phase observations, respectively; \( \varepsilon_0 \), \( m \) and \( e \) express vacuum dielectric constant, electron mass constant and electron charge constant; \( \text{STEC} \) is the line integral of electron density along the electromagnetic wave propagation path from satellite to receiver; the parameters \( B_1 \) and \( B_2 \) are the hardware delay biases of receiver and satellite. It is assumed that the hardware delay biases of all receivers and satellites are already estimated in advance; all the ambiguities information have been solved out by other methods (such as network RTK method) [5]; and the coordinates of receivers and satellite have been measured accurately.

Central processing server collects the observation data of all monitoring stations, and then extracts each observation data into a quintet as the basis for subsequent calculation. The quintet includes \([ \text{lon}, \text{lat}, \text{STEC}, \chi, \text{Az} ]\), indicating [longitude of IPP, latitude of IPP, STEC, zenith angle, azimuth angle].

2.2. Vector Ionospheric Delay Coefficient Fitting
If the ionospheric shell is considered anisotropic, it is possible to obtain different STECs with different \( \text{Az} \) at same IPP when the vertical TEC (VTEC) and \( \chi \) are the same, which is expressed as equation (4):

\[
\text{STEC} = \sec \chi [\text{VTEC} + f(\text{Az})]
\]

We can use polynomial function to fit \( f(\text{Az}) \), then equation (4) is transformed into equation (5):

\[
\text{STEC} = \sec \chi \sum_i \sum_j E_{ij} (\text{lat} - \text{lat}_i)(\text{lon} - \text{lon}_i) + a_1 \text{Az} + a_2 \text{Az}^2
\]

where \( \text{lon}_0 \) and \( \text{lat}_0 \) are the longitude and latitude of the grid point; \( m \) and \( n \) are the maximum order of polynomials; \( E_{ij} \) is the coefficient of each polynomial item; \( a_1 \) and \( a_2 \) are the azimuth correction factors. \( E_{ij}, a_1 \) and \( a_2 \) can be obtained by fitting all the observed IPPs near the grid point, then the correction parameter of the grid point is shown as equation (6):

\[
\sum i, j (d\tau_i, d\tau_{z1}, d\tau_{z2}) = \frac{40.31}{E_{ij}} [a_1, a_2]
\]

Finally, the vector ionospheric correction parameter table covering the target area can be obtained by fitting all grid points. The vector ionospheric products can be broadcasted through satellite, radio, or Internet. When broadcast by satellite/radio, the parameters of each grid node occupy 16 more bits than scalar correction; When broadcast through Internet, all the vector ionospheric products can be broadcast by a-GNSS system [6].

2.3. Ionospheric Correction Using Vector Ionospheric Product for Single Frequency User
Figure 2 shows the schematic diagram of user IPP and grid. The user IPP is represented by \( p \), and the position of four grid points around the user IPP is represented by \( p_i (i = 1 \sim 4) \); The vector ionospheric correction parameters broadcast through satellite or Internet are represented by \( d\tau_i \); The distance weights between the IPP and the four grid points are represented by \( \omega_i \) respectively. Then the vector ionospheric correction of the IPP can be obtained by formula (7):

\[
\sum_i \omega_i d\tau_i, d\tau_{z1} = \frac{4}{\sum_i \omega_i}, d\tau_{z2} = \frac{4}{\sum_i \omega_i}
\]

The pseudo-range ionospheric correction is obtained by formula (8):

\[
I\alpha_p = \sec \chi_p (d\tau_{z1} + d\tau_{z2} \cos A\alpha_p + d\tau_{z2} \sin A\alpha_p)
\]

where \( \chi_p \) is the zenith angle of the user IPP, and \( A\alpha_p \) is the azimuth angle.
3. Experimental Verification Results
We used actual GPS observation data of Global Navigation Satellite System Earth Observation Network of Japan (GEONET) [7] to verify the vector ionospheric correction method, thus showing the different effects compared with the scalar ionospheric correction technology. The test area is selected as four grid points around Tokyo, Japan: p1= [35°N 135°E], p2= [35°N 140°E], p3= [37.5°N 135°E], p4= [37.5°N 140°E]. The maximum order of polynomial is set as m=2, n=2. GEONET has more than 300 ground stations in the area near Tokyo. We used the observation data from January 1 to January 30, 2014 for testing. The Ionospheric TEC parameters of these observation data were calculated [8], and some data are randomly selected as user observation data, that is, verification set, and the rest data are used as observation data of monitoring stations. 100 groups of observation data were selected every day for 3000 rounds of testing. The correction error of each round is shown in figure 3. Overall, the average correction error of scalar ionosphere correction is 0.555m, and the average correction error of vector ionosphere correction is 0.2754m, which is 0.2796m less than that of scalar ionosphere correction, the optimization ratio is about 50%.

Figure 3. Comparison of ionospheric correction errors.

4. Conclusion
The vector ionospheric delay correction algorithm designed in this paper can effectively improve the ionospheric correction error caused by the TEC contribution of plasma layer. The testing results show that the correction error of the vector ionosphere delay correction algorithm is reduced by about 50% compared with the scalar algorithm. However, the new method requires additional broadcast message data and additional resources of storage and calculation, and requires more monitoring stations. It may
become one of the develop directions of navigation augmentation system in the future and has some application value.

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