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Real-time Monitoring and Prediction of Ionospheric Electron Content by Means of GPS† ⋆

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Abstract GPS can be used for high-precision, real-time monitoring of variations in the ionospheric total electron content (TEC), which is important for the ionospheric delay correction to single-frequency GPS receivers, the monitoring of ionospheric activities, and the study of the regularities of solar activity. The establishment of the Shanghai Comprehensive GPS Application Network provides real-time monitoring of the ionospheric variations in the Yangtze River delta region with valuable data. By using continuous observational data from dual-frequency GPS receivers, nearly real-time monitoring and prediction of the ionospheric total electron content of this region is achieved with internal and external agreements and accuracy of 30-minute extrapolation better than 0.4 m.

Key words: astrometry: GPS—Earth

1. INTRODUCTION

Large and small solar flares in recent years interfered or even interrupted the propagation of radio and television signals and the high-energy particle streams they emit severely threaten the safety of space vehicles and astronauts[1]. One of the main factors affecting the propagation of radio signals is the ionospheric delay, for example, the effect on GPS signals going through the ionosphere is as great as 100 m. This is not negligible for high-precision GPS positioning and navigation, hence high-precision monitoring and prediction of ionospheric

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variations are of practical importance. A commonly used method is to monitor the ionospheric response by the altimeter, but during a solar flare the absorption in the D-layer is so serious that the back wave can not be received by the altimeter, so it is difficult for the altimeter monitor the entire ionospheric sudden event. Now, along with progress in the GPS technique, the dual-frequency GPS receiver plays an important role in the monitoring of ionospheric activities[2]. It can measure the ionospheric electron content and its variation even under circumstance of severe solar and earth magnetic field disturbances. And it offers an all-weather and uninterrupted monitoring, which is important not only for the ionospheric delay correction of single-frequency GPS receivers, but also for the real-time monitoring of ionospheric sudden events. Meanwhile, it is important to build a high-precision ionospheric grid model to realize the GPS monitoring of ionospheric activities. In 1998, the International GPS Service (IGS) decided formally to offer the ionosphere service, and to release global real-time grid ionospheric information. The main parameters of the ionospheric information (ionospheric electron content or electron density) are the altitude, local time, intensity of solar activity, season, position of station, and so on and these parameters have very strong space-time correlations. The information released by IGS is global in character and has a low resolution. It does not report precise local ionospheric variation and is unable to make local predictions.

The establishment of the Shanghai Comprehensive GPS Application Network provides real-time monitoring of the ionospheric variations in the Yangtze River delta region with firsthand data. Using dual-frequency GPS observational data, we have built a grid ionospheric model (GIM) of the Yangtze River delta region to monitor and predict the ionospheric total electron content of this region. The precision of the prediction will be evaluated and analyzed below.

2. METHODS FOR MONITORING IONOSPHERIC ELECTRON CONTENT

At present, GPS ionospheric monitoring uses the single-layer grid ionospheric correction models[3,4] (those based on dual-frequency GPS data being the most effective, such as the Klobuchar model and the VTEC (vertical total electron content) model). The Klobuchar model takes the ionospheric delay at night to be a constant 5 ns, and takes the daytime delay as the positive part of a cosine function. The error of this model is about 30-40% of the total amount, and the model is generally adopted as the high-precision regional ionospheric model. The single-layer grid ionospheric model assumes that all the free electrons in the ionosphere are concentrated in an infinitely thin layer, at the height of the expected maximum electron density, of about 300—400 km. In this model, via a mapping function, the total electron content in a slant path is projected to the height of the single spherical shell to obtain the VTEC in the shell, and the overhead ionospheric delay of the user is obtained by interpolating these grid data. Generally, 2-4 hours of observational data are used to produce the VTEC value at the epoch, then by substituting such values into the VTEC model, the corresponding parameters are obtained. And this completes the grid ionospheric model for the region.

Information on the ionospheric electron content is derived by the combined processing of two groups of observation equations of the carrier phase and pseudo distance, taking account of the ambiguity of number of cycles. The hardware delay error of the GPS system includes the hardware delay errors of the satellite and the GPS receiver, which will bring about a systematic error of the order of meters to the ionospheric delay. The detailed procedure of the derivation has been given in Refs.[5-7].

Methods to build the regional grid ionospheric model with VTEC values based on dual-frequency GPS data include the following:

(1) The method of multiquadric function fitting[4,8]

In 1977, Hardy proposed the method of multiquadric function fitting, and applied it to analyze the vertical deformation of the earth crust, fitting the altimetric rate surface, and so on. Here, we will apply it to the GPS grid ionospheric model. The fitting model is

$$\mathrm{VTEC}(B,L)=\sum_{i=1}^{n}a_iQ(B,L,B',L')\,, \tag{1}$$

in which $\mathrm{VTEC}(B,L)$ is the vertical electron content at the puncturing point (geodetic coordinates (B,L)), B', L' are the geodetic coordinates of the grid node, and the kernel $Q(B,L,B',L')$ is the positive quadric function,

$$Q(B,L,B',L')=[(B-B')^2+(L-L')^2\cos^2 B'+\varepsilon^2]^\beta\,, \tag{2}$$

in which ε^2 and β are smoothing factors (after some trial and error, we got ε^2=0.01, β=0.5). Assuming that at each epoch there are m puncturing points (B, L) and n grid nodes (B', L'), then every grid node is taken as the central point of the kernel function, and the model calculation is made once at each epoch. When there is a lot of GPS data, Eq.(1) can be re-written as:

$$v_{\mathrm{VTEC}}=Qa\,, \tag{3}$$

i.e.,

$$\begin{bmatrix} v_1(B_1,L_1)_{\mathrm{VTEC}} \\ v_1(B_2,L_2)_{\mathrm{VTEC}} \\ \vdots \\ v_1(B_m,L_m)_{\mathrm{VTEC}} \end{bmatrix}=\begin{bmatrix} Q(B_1,L_1,B_1',L_1') & \cdots & Q(B_1,L_1,B_n',L_n') \\ \vdots & & \vdots \\ Q(B_m,L_m,B_1',L_1') & \cdots & Q(B_m,L_m,B_n',L_n') \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}. \tag{4}$$

The error equation is:

$$\Delta v=Qa-v_{\mathrm{VTEC}}\,. \tag{5}$$

So we have

$$a=(Q^TP_vQ)^{-1}Q^TP_vv\,, \tag{6}$$

and the VTEC at grid point (B_h', L_h') is obtained. Thus,

$$\mathrm{VTEC}_h=Q_h^ta\,, \tag{7}$$

in which $Q_h^t=(Q_{h1},Q_{h2},\cdots Q_{hi})$.

(2) The VTEC method[3]:

This method takes VTEC as a function of the differences in latitude and sun's hour angle. It is expressed as:

$$\mathrm{VTEC}(\varphi,\lambda)=\sum_{i=0}^{n}\sum_{j=0}^{m}E_{ij}(\varphi-\varphi_0)^i(S-S_0)^j\,, \tag{8}$$

in which (φ, λ) are the geographic latitude and longitude of the ionospheric puncturing point, (φ_0, λ_0) are the geographic latitude and longitude of the center of the measuring region, S_0 is the sun's hour angle at the time t_0 in the middle of the time interval, $(S - S_0) = (\lambda - \lambda_0) + (t - t_0)$, and t is the observing time. If the measuring region does not extend more than a continent, n and m are taken to be 2 and 4, respectively.

(3) The method of distance weighting:

This method incorporates a constraint by taking as weight the distance from the puncturing point. It adopts the interpolation weighting function of WAAS (Wide Area Augment System), and regards the ionospheric delay at the puncturing point as a function of the positions (ϕ_i, λ_i) of its surrounding 4 grid points. The exact function can be found in Refs.[3,9,10].

3. RESULTS AND DISCUSSION

3.1 GPS Observational Data

The Shanghai Comprehensive GPS Application Network has been in operation since June 2002. It consists of 14 ground GPS standard stations and a central processing station, and it is equipped with Ashtech dual-frequency GPS receivers with sampling interval set at 30 sec. The distribution of the GPS stations, 5 in the Shanghai area and 9 in the Jiangsu, Zhejiang and Anhui areas surrounding Shanghai, basically covers the Yangtze river delta region (see Fig.1), and the central processing station is located at Shanghai. This GPS network carries out 24-hour continuous observations. It can make real-time monitoring and prediction of the ionospheric total electron content for this region, as well as the ionospheric delay correction to single-frequency GPS receivers.

3.2 Results of Nearly Real-time Monitoring

Using the continuous data of the 14 GPS observing stations, we have built and realised $0.2° \times 0.2°$ grid ionospheric models using respectively the methods of multiquadric function fitting, VTEC and distance weighting. With these we can calculate the ionospheric vertical total electron content (VTEC) at any grid point. Fig.2(a) is the 3-dimensional distribution of the vertical electron content for the Shanghai Pudong station and the GPS PRN21 satellite (for Beijing Time 8:00-12:00), and Fig.2(b) is the distribution of the vertical electron content in the Yangtze River delta region and its contour map on 2003 September 7, at Beijing time 14:00. Fig.2(b) exhibits clearly the VTEC distribution over the $0.2° \times 0.2°$ grid points of the Yangtze River delta region, from which we can find that in this region the ionospheric vertical electron content increases towards the south-east corner, where it reaches 110 TECU, (1 TECU $= 1 \times 10^{16}\, e/m^2$), for instance, 113 TECU at the grid point (123E, 28N). Limited by the length of this paper, we have not listed the distribution of the electron content for

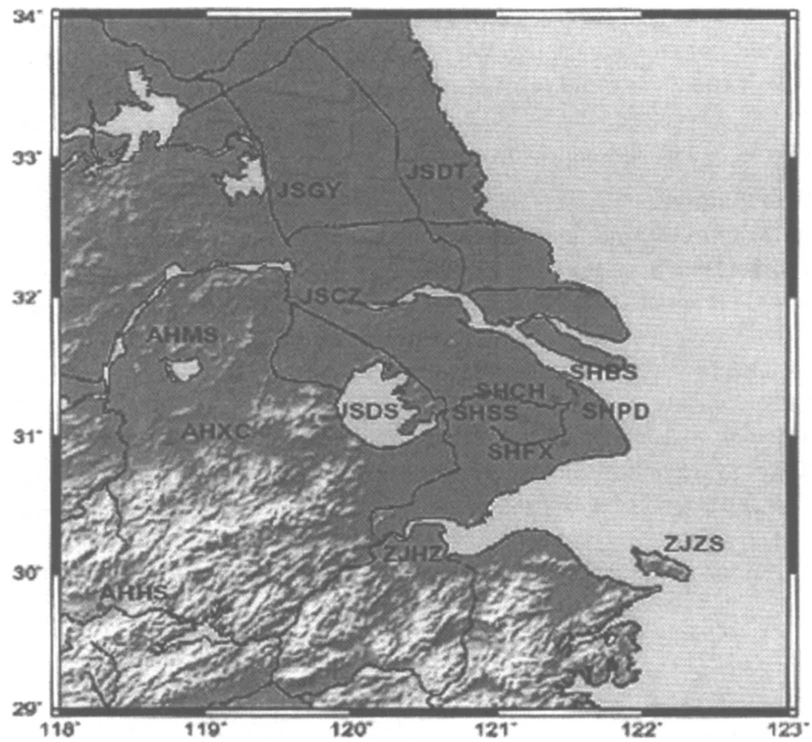


Fig. 1 Locations of the stations of the Shanghai Comprehensive GPS Application Network

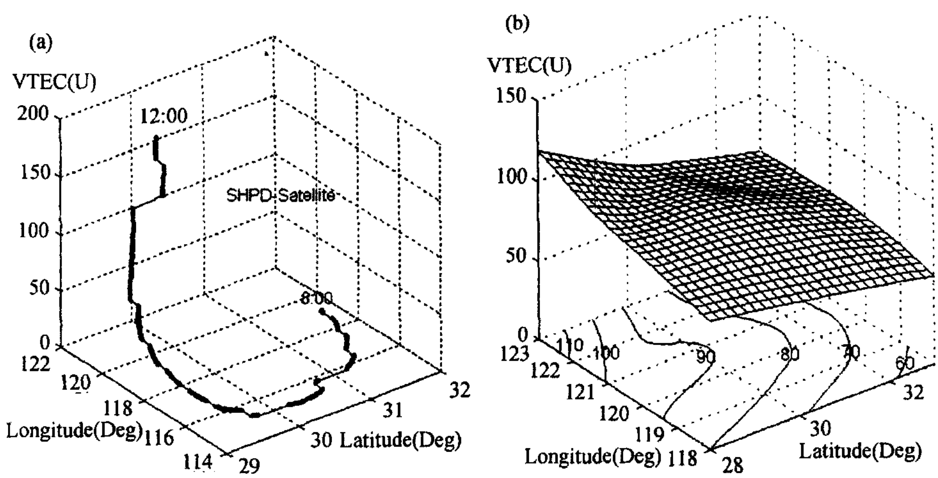
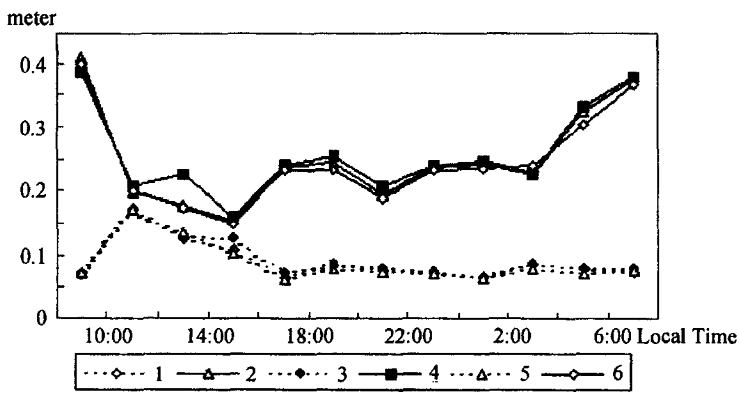


Fig. 2 3-dimensional distribution of VTEC (at Local Time 8:00-12:00) for the Shanghai Pudong station and GPS PRN21 satellite (a) and the distribution of VTEC in the Yangtze River delta region (b) different times. Generally, the amplitude of the daily variation of the VTEC at a given grid point is about 30 TECU. Now, nearly real-time monitoring of the ionospheric electron content requires nearly real-time orbit prediction. At present, the IGS's ultrarapid product IGU provides nearly real-time orbits. We calculated the electron content at the grid points using respectively the ultra rapid orbit of IGU and the precise orbit of IGS, and we obtained the same results. Therefore, the GPS data can be used for nearly real-time monitoring of the ionospheric total electron content and of its variation.

3.3 Precision Analysis

The accuracies of internal and external agreements can reflect the monitoring precision of the electron content at a grid point. The accuracy of internal agreement is calculated with the residual errors of the model fitting, and the accuracy of external agreement is the mean RMS error of the electron content (or delay) in the zenith direction. To compare the three methods and to verify the reliability of the results, we have calculated, separately, the internal and external accuracies for the three different methods. The obtained results are basically consistent with each other (Fig.3). The average accuracy of internal agreement of 0.1 m and the average accuracy of external agreement of 0.3 m indicate that the three methods are all fairly good for the monitoring of the ionospheric electron content at a grid point.

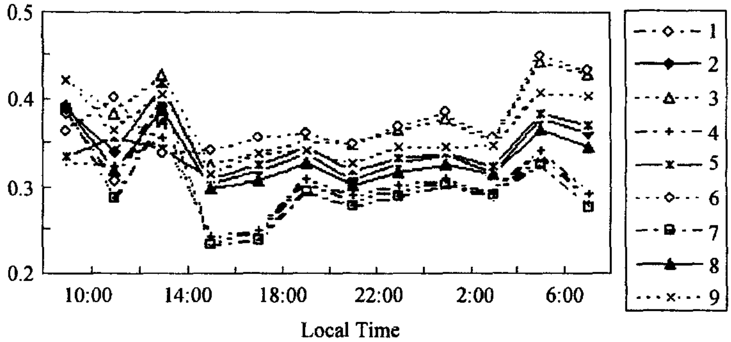


(1,3 and 5 are the accuracies of internal agreement of the multiquadric function fitting, VTEC and distance weighting methods, respectively; and 2,4 and 6 are the corresponding accuracies of external agreement.)

Fig. 3 The accuracies of internal and external agreements of TEC for different grid ionospheric models

Moreover, with the grid ionospheric model, we can extrapolate and predict the ionospheric electron content at a given grid point from the 2-4 hours GPS observational data, and promptly deliver it to the user. To evaluate the accuracy of the predicted value, we made 10, 20 and 30-minute predictions, and found the average accuracies to be 0.275 m, 0.332 m and 0.391 m, respectively (see Fig.4).

In summary, GPS can be used for nearly real-time monitoring of the ionospheric electron content and its extrapolation or prediction. The accuracies of internal and external agreement, and the accuracy of extrapolation, are comparable for models based on the



(1, 2 and 3 are, respectively, the accuracies of 10, 20 and 30-minute extrapolations with the multiquadric function fitting method; 4, 5 and 6, the same with the VTEC method; and 7, 8 and 9, the same with the distance weighting method)

Fig. 4 The extrapolation accuracy of TEC for the three grid ionospheric models

methods of multiquadric function fitting, VTEC and distance weighting. The internal and external agreements are both better than 0.3 m, and the accuracy of a 30-minute extrapolation is better than 0.4 m. Ionospheric sudden changes occur mainly on small scales, so the grid ionospheric model should have a rather high space-time resolution. The regional grid ionospheric model built in this paper has a rather good practical value for the nearly real-time monitoring and prediction of ionospheric sudden changes in the Yangtze River delta region.

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