Estimation Algorithm of Ionospheric Delay Correction Parameters Based on Neural Network

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Abstract. Aiming at the difficulty of separating the ionospheric delay error in the user pseudoranging observations of a single-frequency receiver, this paper proposes an error separation method based on BP neural network. The receiver's observation data for a continuous week is used as a training sample, and the time in the sample is the satellite altitude, azimuth and pseudoring observations are used as the input unit of the BP neural network. The high-precision GIM provided by CODE is used to calculate the corresponding ionospheric delay error, and it is used as the output unit to train the BP neural network. At the end of the thesis, the single-frequency PPP model that uses parameter estimation in the ionosphere is discussed. Finally, the positioning accuracy that this model can achieve is verified through actual calculation examples.

1. Introduction
GPS Precision Point Positioning (PPP) is a method of obtaining real-time or post-event high-precision positioning on a global scale by using the precise ephemeris and precise satellite clock offset of GPS satellites and the observation data collected by a single GPS receiver. Because of its high efficiency, flexibility and precision, PPP technology has attracted more and more attention. Using dual-frequency carrier phase observations, GPS precise single-point positioning can obtain centimetre-level static positioning accuracy and decimetre-level dynamic positioning accuracy. The integrated method of system optimization and parameter estimation is a non-linear system steady-state optimization method proposed by the research team led by Roberts [1]. It can obtain the optimal solution of the system (controller design) when there is a difference between the model and the actual process. However, the ISOPE method needs to perturb the actual process to obtain the derivative required for optimization. The perturbation has an adverse effect on the actual process, which is not allowed in production, and it will significantly increase the invalid waiting of the algorithm. In order to overcome this shortcoming, this paper introduces the multi-layer forward neural network into the neural network and proposes two improved algorithms. Simulations show that the new method significantly reduces the number of set point changes and speeds up the convergence.

2. The ionosphere adopts model correction
The observation equation of single-frequency precision single-point positioning is:

$$C_1 = \rho'_e + c \left( dt_e - dt^e + T_{gd} \right) + d_{orb} + d_{trop} + d_{ion} + d_{rel} + c \left( C_1 \right)$$

(1)
\[
\Phi_1 = \rho^* + c \cdot (dt_r - dt^*) + d_{\text{orb}} + d_{\text{trop}} - d_{\text{ion}} + d_{\text{rel}} + \lambda_1 \cdot N_1 + \varepsilon (\Phi_1)
\] (2)

Among them: \(C_1\) is the C/A code pseudo ring observation value; \(\Phi_1\) is the L1 phase observation value obtained by the receiver; \(\rho^*\) is the geometric distance between the satellite and the receiver; \(c\) is the speed of light; \(dt_r\) is the receiver clock error; \(dt^*\) is the satellite clock Difference; \(d_{\text{orb}}\) is the orbit error; \(d_{\text{trop}}\) is the tropospheric error; \(d_{\text{ion}}\) is the ionospheric error; \(d_{\text{rel}}\) is the relativistic effect; \(\lambda_1\) is the wavelength of the L1 carrier; \(N_1\) is the ambiguity of the L1 phase; \(T_{\text{gg}}\) is the satellite hardware delay; \(\varepsilon(C_1)\) and \(\varepsilon(\Phi_1)\) They are respectively the noise error of the observed value of C/A and the observed value of L1 phase. Since the combination of carrier phase observations or code pseudoring observations cannot eliminate the effect of ionospheric delay in single-frequency precision single-point positioning, the equations (1) and (2) must be corrected \(d_{\text{ion}}\) in other ways. The current ionospheric correction models mainly include the Klobuchar model of broadcast ephemeris, the global ionospheric grid model or spherical harmonic correction model provided by IGS, and the observation data of multiple reference stations in a certain area can also be used to fit an ionospheric correction model.

2.1. Vertical delay

\[
I_z(t) = \begin{cases} 
A_1 + A_2 \cdot \cos \left( \frac{2\pi \cdot (t - A_3)}{A_4} \right) & |t - A_3| < A_4 / 4 \\
A_2, & \text{otherwise}
\end{cases}
\] (3)

In the formula, \(I_z\) is the vertical delay in seconds, \(t\) is the intersection between the receiver and the satellite and the ionosphere (M) in seconds, \(A_1 = 5 \times 10^{-9} \text{ s}\) is the vertical delay constant at night, and \(A_2\) is the daytime cosine the amplitude of the curve is obtained from the \(\alpha_n\) coefficient in the broadcast ephemeris

\[
A_2 = \begin{cases} 
\sum_{n=0}^{3} \alpha_n \cdot \phi_m^n & A_2 \geq 0 \\
0 & A_2 < 0
\end{cases}
\] (4)

When \(A_3\) is the place corresponding to the pole of the cosine curve, it is generally taken as 50400s (that is, 14:00), and \(A_4\) is the period of the cosine curve, which is obtained from the \(\beta_n\) coefficient in the broadcast ephemeris. \(\phi_m\) And \(\lambda_i\) are the latitudes of the earth at point \(M\) (The unit is a semicircle) and longitude (the unit is radians).

\[
A_4 = \begin{cases} 
\sum_{n=0}^{3} \beta_n \cdot \phi_m^n & \phi A_4 \geq 72000 \\
72000 & \phi A_4 < 72000
\end{cases}
\] (5)

\[
\lambda_i = \lambda_u = \frac{\psi \cdot \sin A}{\cos \phi_i}
\] (6)
\( \lambda_u \) is the latitude of the earth at the receiver (unit is a semicircle), \( \psi \) is the angle between the centre of the receiver and \( M \) (unit is a semicircle), \( A \) is the azimuth angle of the satellite (unit is radians), where \( \lambda_u \) is the unit, it is a semicircle. \( \phi_u \) is the latitude of the earth at the receiver (unit is a semicircle)?

\[
\phi_i = \begin{cases} 
\phi_u + \psi \cdot \cos A & \left| \phi_i \right| \leq 0.416 \\
+0.416 & \phi_i > 0.416 \\
-0.416 & \phi_i < -0.416 
\end{cases}
\] (7)

2.2. Tilt factor

\[ F = 1.0 + 16.0 \times (0.53 - E)^3 \] (8)

2.3. Application value of ionospheric delay

\[ I(t) = F \cdot I_z(t) \] (9)

Since the correction efficiency of the Klobuchar model is only 50-60%, the residual error is still a few meters after the ionospheric delay is corrected using the Klobuchar model, so the positioning result is poor. IGS's data analysis centre CODE provides correction coefficients in the form of ionospheric spherical harmonics worldwide [2]. Users can use the spherical harmonic coefficients provided by this spherical harmonic coefficient file to calculate the ionospheric delay at any position at any time.

3. Ionospheric parameter estimation

The concept of the ionospheric single-layer model (SLM) is usually introduced when conducting ionospheric research. The single-layer model (SLM) is based on the assumption that all free electrons in the ionosphere are concentrated at the height of the ionospheric centre of mass. A thickness is infinite on the thin monolayer, 50% of the electrons are above and below this height [3]. The ionospheric mapping function and the puncture point are related. At the puncture point, the estimated electron content on the GPS signal propagation path is TEC. Single layer mapping function:

\[
\sin z' = \frac{R}{R + h} \sin z
\]

\[
F(z) = \frac{1}{\cos z} = \frac{1}{\sqrt{1 - \sin^2 z'}}
\] (10)

The broadcasting ephemeris mapping function is:

\[
F(E) = 1.0 + 16.0 \times (0.53 - E)^3
\]

\[
F(h) = 1.0 + 0.516 \times (1.6745 - h)^3
\] (11)

Among them, \( R=6378\text{km} \) is the radius of the earth, \( H \) is the height of a single layer, \( z \) is the satellite zenith angle, \( z' \)is the satellite zenith angle at the puncture point, \( E \) is the satellite altitude angle (in units), and \( h \) is the satellite altitude angle (The unit is radians). Figure 1 shows the ionospheric single-layer model [4]. The ionospheric parameter estimation model introduces unknown parameters in the positioning calculation together with position parameters for estimation calculation. Introduce a mathematical model of the zenith ionospheric delay at the station as an unknown parameter:
\[ C_i = \rho_i^s + c \cdot dt_i + F \cdot d_{ion}^{\text{incoh}} + \varepsilon(C_i) \]
\[ \Phi_i = \rho_i^s + c \cdot dt_i - F \cdot d_{ion}^{\text{incoh}} + \lambda_i \cdot N_i + \varepsilon(\Phi_i) \]  

(12)

Where F is the ionospheric mapping function.

Figure 1. Ionospheric monolayer model.

This paper introduces two ionospheric parameters in the calculation, and the function of ionospheric delay is expressed as:

\[ I = F \cdot A \cdot d_i^{A \ion} + F \cdot E \cdot d_i^{E \ion} \]  

(13)

The corresponding observation equation is:

\[ C_i = \rho_i^s + c \cdot dt_i + F \cdot A \cdot d_i^{A \ion} + F \cdot E \cdot d_i^{E \ion} + \varepsilon(C_i) \]
\[ \Phi_i = \rho_i^s + c \cdot dt_i - F \cdot A \cdot d_i^{A \ion} - F \cdot E \cdot d_i^{E \ion} + \lambda_i \cdot N_i + \varepsilon(\Phi_i) \]  

(14)

Among them, F is the ionospheric mapping function; A is the azimuth angle of the satellite at the station; E is the altitude angle of the satellite at the station; \( d_i^{A \ion} \), \( d_i^{E \ion} \) is the introduced unknown parameter.

4. Ionospheric error separation model based on neural network

4.1. Principle of BP Neural Network

BP neural network is one of the most important networks in artificial neural networks. It embodies the essence of artificial neural networks. Its essence is to use the sum of squares of network errors as the objective function, and the algorithm to find the minimum objective function according to the gradient descent algorithm [5]. According to the Kolmogorov theorem, any continuous function in a closed interval can be approximated by a single hidden layer BP network, that is, a three-layer BP neural network can complete any mapping from N to M dimensions. The topological structure is shown in Figure 2.
4.2. Determination of input factors for ionospheric error separation model

In order to increase the accuracy of the separation of the ionospheric delay error, the BP neural network model in different periods should use the data samples of different periods as training samples, and the ionospheric VTEC data is relatively stable in a short period of time (such as 2h), so when using the method proposed in this paper to separate the ionospheric delay error of pseudoring observations, the 24h of a day is divided into 12 periods with a period of 2h. In summary, this paper uses a three-layer BP neural network to establish the ionospheric error separation model of the pseudo-range observations, selecting time, pseudo-range, visible star altitude angle and azimuth angle to separate the ionospheric error from the pseudo-range observations. Factors with high correlation are used as input factors of the neural network.

5. Case design

The modelling data mentioned in this article all use the data of JSCORS on November 19, 2020 from 00:00 to 4:00 (including the puncture point (IPP) number, station location, IPP longitude, IPP latitude, and observation time, VTEC true value), and divide it into modelling data and model data inspection groups. These stations are evenly distributed in the range of 30° to 35° north latitude and 116° to 123° east longitude, with a total of 68 stations [6]. The method of obtaining the true value of the ionospheric puncture point VTEC in these data is the dual-frequency GPS observation value or extracting it from the CORS data using the phase smoothing pseudoring method based on the CORS observation data. Divide it into a modelling data group and a test data group, select 3 of the data sets at the station for modelling, and check the data from the other 33 stations.

In this project example, we select a total of 3200 sets of data from 0 to 1 o'clock and 2 to 3 o'clock. According to the method described above, first use the least square method to find the other eight parameters of the quadratic polynomial model, and substitute them to obtain the quadratic polynomial. The model value. Then the median error calculation is performed to obtain the median error of the model data and the test data [7]. Use the obtained quadratic polynomial and the residual of the true value to continue the establishment of the neural network fusion model, and finally compare the errors in the modelling results from 0 to 1 and 2 to 3.

Figure 3 shows the comparison of the errors between the binomial model and the fusion model from 0 to 1. It is obvious that the VTEC error of the fusion model of almost all stations is smaller than that of the polynomial model. Figure 4 is a comparison of the errors in the models from 2 to 3. It can also be clearly seen that the VTEC errors of the fusion models of almost all stations are smaller than those of the polynomial model, and the median error curve of the fusion model is more stable than that of the
polynomial model. The peak value of the maximum median error value is lower than the second-order polynomial, which can better predict the total ionospheric electron content.

![Figure 3. Comparison of errors in the two models at 0-1.](image1)

![Figure 4. Comparison of errors in the two models at 2-3.](image2)

We put the errors in the models of all stations in Table 1 for comparison, and it can be compared from 0 to 1, and 2 to 3 that the errors in the fitting of the neural network fusion model are increased by 18.1 compared to the second-order polynomial accuracy 22.5%.

| Time              | 2-DPM | Fusion model | Improved accuracy of fusion model (%) |
|-------------------|-------|--------------|---------------------------------------|
| 0:00-1:00         | 2.471 | 2.024        | 18.1                                  |
| 2:00-3:00         | 3.044 | 2.359        | 22.5                                  |

6. Conclusion
Aiming at the difficulty of separating the ionospheric delay error of the single-frequency receiver, this paper applies the BP neural network to the separation of the ionospheric delay error of the pseudo-range observation value of the single-frequency receiver. Taking time, satellite altitude angle, azimuth angle, and pseudorange as the related factors of ionospheric delay error, a separation model of ionospheric delay error based on BP neural network is proposed. Case analysis shows that the accuracy of the fusion model is improved by 18.1%.

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