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Combined Positioning Algorithm and Accuracy Analysis for BD2/GPS Positioning System

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Abstract

To restrain the error sources, namely ionospheric delay and tropospheric delay, in the solution method of BD2/GPS combined positioning system, we introduce the Klobuchar model and Hopfield model to correct them. By simulating and testing the real data practically, the result indicates that ionospheric delay can be significantly decreased with the model. However, it is impossible to eliminate the tropospheric delay. Through using satellite selection algorithm for Multi-system, the satellite data which elevation of the satellite is less than 10 degrees can be precluded effectively, which makes it possible for further improvement in positioning accuracy.

Keywords: *BD2, GPS, Klobuchar model, ionospheric delay*

1. Introduction

Both GPS satellites and BD2 satellites are employed by BD2/GPS combined system, which improves significantly the accuracy and reliability of the navigation function. In these two systems, the ionospheric delay and the tropospheric delay can be decreased using several methods which have already got the appreciable results. However, due to the short operating time of BD satellite system, the research of error sources and modeling methods are still not enough [1]. We found that as an effective model (Klobuchar model) was used in GPS system, the Klobuchar model can be introduced into the combined satellite system either. While some assist strategies are necessary to complement, means that the ionospheric delay can be restrained effectively by using the Klobuchar model and satellite selection algorithm should be adopted to reduce the tropospheric delay.

2. BD-2/GPS Combined System Solver Model

By using BD2/GPS combined machine, we can not only achieve global, all-meteorology and high precision measurement of the movement with seven-dimension status vector and three-dimension stance parameters, but also can take advantage of multi-satellite data sources to improve the positioning accuracy[2]. The fundamental of GPS and BD2 is measuring the time when they are transmitted from known-location satellite to receivers. If a receiver can receive both GPS and BD2 signals, it would have gathered more observable parameters to improve the positioning accuracy.

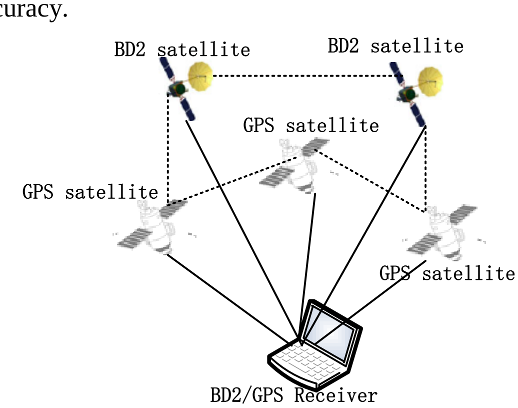

Fig. 1. Diagram of BD2/GPS combined system

As is shown in Fig.1, BD2/GPS receiver can also receive BD2 signals and GPS signals. This combined system can significantly make contribution to the further improvement in positioning accuracy.

2.1 Data Fusion Based on Pseudo range Combined Positioning

When using the method of pseudo range position solutions, the parameters both in BD2 and GPS can be combined to complete solutions. The information, including Satellite ephemeris, the time of receiving signals, Doppler information, can be obtained from receiver channels. By combining with pseudo range equations, we can solute the users' position. This performance of combined method is superior to that single solution method.

The observation equations of BD2 and GPS system can be expressed respectively as follows [18]:

$$\mathbf{Y}_{GPS} = \mathbf{A}_{gps}\mathbf{X}_{GPS} + \boldsymbol{\varepsilon}_{GPS} \quad (1)$$

$$\mathbf{Y}_{BD2} = \mathbf{A}_{BD2}\mathbf{X}_{BD2} + \boldsymbol{\varepsilon}_{BD2} \quad (2)$$

Where $\mathbf{Y}$ is m $\times$ 1 dimensions observation vector, $\mathbf{A}$ is state transition matrix, $\mathbf{X}$ is user state vector, ε is observation error vector. By combining equation (1) and equation (2), the pseudo range observation equation for BD2/GPS combined system can be obtained as [18]:

$$\begin{bmatrix} \mathbf{Y}_{GPS} \\ \mathbf{Y}_{BD2} \end{bmatrix} = \begin{bmatrix} \mathbf{A}'_{GPS} & \mathbf{1}_{GPS} & \mathbf{0}_{GPS} \\ \mathbf{A}'_{BD2} & \mathbf{0}_{BD2} & \mathbf{1}_{BD2} \end{bmatrix} \mathbf{X}' + \begin{bmatrix} \boldsymbol{\varepsilon}_{GPS} \\ \boldsymbol{\varepsilon}_{BD2} \end{bmatrix} \quad (3)$$

From the equation (3), we know that if given the information of the observation satellites, we need solve at least 5 parameters.

2.2 Mathematical Foundation of Pseudo range Positioning

The basic equation of the pseudo-random code ranging is showed as follows [17]:

$$\rho = c\tau' = c(\tau + \delta + n\mathrm{T}_{C/A}) = R + c\delta t \quad (4)$$

Where R is the real distance between receiver and satellite, and c is the velocity of electromagnetic wave propagation, τ' is local phase delay, τ is code phase[4][5], δt is satellite clock offset, $T_{C/A}$ is transmission cycle of C/A code and ρ presents pseudo range value. If the distances between unknown point and some space known points are measurable, we can get the coordinate of the unknown point accord with the position of known point and the distances between known points and unknown points in the same coordinate system, which is the basic mathematical thought of propagation positioning. The pseudo range can be obtained with Pseudo-random code phase measurements or Carrier phase measurements. The equation (4) can be rewritten as follow[17]:

$$\rho_k^j = c\tau' = R_k^j + cd\tau_k - cd\tau^j + d\rho_{ion}^j + d\rho_{trop}^j \quad (5)$$

Where ρ_k^j is the pseudo range between receiver k and satellite j, which can be directly measured by receiver, and R_k^j is the real distance between receiver k and satellite j, and τ' is the propagation time of signal measurement, and $d\tau_k$ is the receiver clock offset, $d\tau^j$ is satellite clock offset which can be obtained with navigation message, $d\rho_{ion}^j$ is ionospheric delay and $d\rho_{trop}^j$ is tropospheric delay. The real distance between receiver k and satellite j can be presented as follow[17]:

$$R_k^j = |\mathbf{X}^j - \mathbf{x}_k| = \sqrt{(\mathrm{X}^j - x_j)^2 + (\mathrm{Y}^j - \mathrm{y}_j)^2 + (\mathrm{Z}^j - z_j)^2} \quad (6)$$

Where X^j is position vector of satellite j in the ECEF coordinate system and $\mathbf{X}^j = [\mathrm{X}^j, \mathrm{Y}^j, \mathrm{Z}^j]^T$, $\mathbf{x}_k$ is position vector of satellite k in the ECEF coordinate system, $\mathbf{x_k} = [\mathrm{x}^j, \mathrm{y}^j, \mathrm{z}^j]^T$ .The ionospheric delay and tropospheric delay can be corrected by models and the satellite clock offset can be corrected by navigation message .The equation (5) can be expressed simply as follow[17]:

$$\rho_k^j = |\mathbf{X}^j - \mathbf{x}_k| + \mathrm{cd}\,\tau_k \quad (7)$$

To get the three-dimension position $[\mathrm{x}^j, \mathrm{y}^j, \mathrm{z}^j]^T$ of the user and the clock offset $d\tau_k$ of receiver, four equations should be provided at least, that four satellites should be visible at least. If the approximate position of receiver is known, the offset between real position and approximate position can be expressed as $\Delta\mathbf{x}_k = [\Delta x_k, \Delta y_k, \Delta z_k]^T$, and the real position of user can be written as $x_k = \tilde{x}_k + \Delta\mathbf{x}_k$, $\tilde{x}_k = [\tilde{\mathrm{x}}^j, \tilde{\mathrm{y}}^j, \tilde{\mathrm{z}}^j]$ .According to the above analysis, the coordinate representation of the equation (7) is showed as following[17]:

$$\rho_k^j = \sqrt{\left(\mathrm{X}^j - \mathrm{x}_k\right)^2 + \left(\mathrm{Y}^j - \mathrm{y}_k\right)^2 + \left(\mathrm{Z}^j - \mathrm{z}_k\right)^2} + cd\tau_k \quad (8)$$

The observation offset equation of the equation (8) can be presented as[17]:

$$\gamma_k^j = \mathbf{I}_k^j \Delta x_k - cd\tau_k - L_k^j \quad (9)$$

Where r_k^j indicates the offset between user k and satellite j, $\mathbf{I}_k^j$ is the unit vector which user k points to satellite j. The unit vector $\mathbf{I}_k^j$ can be expressed as[17]

$\mathbf{I}_k^j = \left[\frac{x^j - \tilde{x}_k}{\tilde{\rho}_k^j}, \frac{y^j - \tilde{y}_k}{\tilde{\rho}_k^j}, \frac{z^j - \tilde{z}_k}{\tilde{\rho}_k^j} \right]$, $\tilde{\rho}_k^j$ is the approximate distance between the user of k and the satellite of j, $\tilde{\rho}_k^j = \left| \mathbf{X}^j - \tilde{\mathbf{x}}_k \right|$ and L_k^j is a constant. $L_k^j = \tilde{\rho}_k^j - \rho_k^j$ .When the number of visible satellites is not less than four, the following equations can be obtained[17].

$$\begin{cases} \gamma_k^1 = \mathbf{I}_k^1 \Delta x_k - cd\tau_k - L_k^1 \\ \gamma_k^2 = \mathbf{I}_k^2 \Delta x_k - cd\tau_k - L_k^2 \\ \quad \cdots \\ \gamma_k^n = \mathbf{I}_k^n \Delta x_k - cd\tau_k - L_k^n \end{cases} \tag{10}$$

The matrix of equations (7) is following [17].

$$\mathbf{V} = \mathbf{AX} - \mathbf{L} \tag{11}$$

Where

$\mathbf{V} = \left[\gamma_k^1, \gamma_k^2, \gamma_k^3, \cdots \gamma_k^n \right]^T$, $\mathbf{L} = \left[L_k^1, L_k^2, L_k^3, \cdots L_k^n \right]$,

$\mathbf{A}^T = \begin{bmatrix} \gamma_k^1 & \gamma_k^1 & \gamma_k^1 & \cdots & \gamma_k^1 \\ -1 & -1 & -1 & \cdots & -1 \end{bmatrix}$, $\mathbf{X} = \begin{bmatrix} \Delta x_k \\ cd\tau_k \end{bmatrix}$

The equation (11) is the measuring equation of navigation pseudo range positioning. The measurement residual V denotes the residual errors without known biases. It usually consists of some slowly changing items and random noises. The former can be got from equivalent user ranging error. The latter's high frequency error is mainly made by the noises of receivers and the errors of quantifies [6].For the reason that the number of satellites which can be observed is different, the different methods should be provided to solve above equations. We can divide them into the following situations:

When the number of observed satellites is equal to 4(n=4), only the random errors can be ignored(V=0)， so the following equation can be acquired[17]:

$$\tilde{\mathbf{X}} = \mathbf{A}^{-1}\mathbf{L} \tag{12}$$

When the number of observed satellites is more than 4(n>4), the following result can be got through Least-squares [17]:

$$\mathbf{A}\tilde{\mathbf{X}} = \mathbf{A}^{\mathbf{T}}\mathbf{L} \tag{13}$$

Solving the equation (12), the value of unknown vector $\tilde{\mathbf{X}}$ can be obtained by [17]:

$$\tilde{\mathbf{X}} = (\mathbf{A}^{\mathbf{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathbf{T}}\mathbf{L} \tag{14}$$

As a matter of fact, when the approximate position of receiver is unknown, we can take it as the Earth's center of mass. Least-squares method for solving process multiple iterations [7-8], the solver results will converge to get the required position.

2.3 The Time and Coordinates Synchronization for BD-2/GPS Combined System

2.3.1 Time synchronization

Due to the differences of height and the method of processing the signals, the locating data at the same time may appear the out-of-synchronization problems when they are received in the receivers. The difference of receiving time [3] between GPS system and BD2 system can be used as the position variables, then we can get the time difference with solving the equations and we can also solve the issue of time reunification by increasing the number of observation satellites. The time transforming formula between BD2 and GPS system is showed as following [17]:

$$t_{GPS} = t_E - \Delta t_{GPS} \tag{15}$$

Where $\Delta t_{GPS} = A_{0GPS} + A_{1GPS} \times t_E$, t_E is the time in BD2 system, A_{0GPS} is the relative difference between GPS system clock and BDT, and A_{1GPS} is the difference between BD2 and GPS in Clock Speed.

2.3.2 Coordinates synchronization

CGCS2000 coordinate is used in BD system, and WGS84 is used in GPS system. CGCS2000 [3] is a new generation of geodetic coordinate system in China, whose definition and the parameters are quite similar to the WGS84 coordinate system. In the literature [3], the difference can be got in the same coordinate between CGCS2000 and WGS84. The transformation between CGCS2000 and WGS84 can be achieved according to its correction parameter.

2.4 The Time and Coordinates Synchronization for BD-2/GPS Combined System

The satellite signal in the communication process can be influenced by the factors including multipath effects and the delay of Ionosphere and Troposphere. At present, it is difficult to eliminate the impact introduced by multipath effects, but we can take precautions for it with Klobuchar model and Hopfield model [9].

2.4.1 The error of Ionospheric delay

The velocity and time of propagation would change when the satellite signal travel Ionosphere above earth. The geometric distance between satellite and receiver is not

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equal to the propagation time of satellite signal multiplying the speed of light, and the difference between them is defined as Ionospheric delay [10]. Klobuchar model is broadly applied to correct the delay of Ionosphere in GPS navigation and positioning, and GPS navigation message also broadcast model parameter to user.

To alleviate the effects of the ionosphere, in general, Klobuchar model can be adopted. This model regards the delay of day's ionosphere [11-12] as positive part of Cosine wave, while it is regarded as constants at night. At 2 PM, ionospheric delay can reach up to maximum. At any time, ionosphere vertical delay can be described as follow [16]:

$$\Delta_i^{j-Iono} = \begin{cases} D_\varepsilon + A_L + \cos\frac{2\pi}{\rho}\left(t-T_p\right), & \left(t-T_p\right) < \frac{p}{4} \\ other \end{cases} \quad (16)$$

Where the delay Δ_i^{j-Iono} is in vertical, t is in unit second of the receiver to the satellite connection and cross the ionosphere at the point M. Here, ionosphere delay D_ε in night equals 5×10^{-9} s, and T_p is the local time [13[14] which correspond to the pole place of Cosine wave, and A_1 is amplitude of day's Cosine curve. A_1 and p can be expressed [16]:

$$A_1 = \begin{cases} \sum_{n=0}^{\delta} \alpha_n \varphi_m, A_1 \geq 0 \\ 0, A_1 < 0 \end{cases},$$

$$P = \begin{cases} \sum_{n=0}^{\delta} \beta_n \varphi_m, P \geq 7200 \\ 7200, P < 7200 \end{cases} \quad (17)$$

Where α_n and β_n are the ionosphere parameters which come from the GPS ephemeris parameters in 4th sub-frame

2.4.2 The error of tropospheric delay

The change of velocity and trace is the main reason of tropospheric delay when satellite signal travels through troposphere. The size of the tropospheric delay error is related to the distance that satellite signal pass through troposphere. So the smaller the elevation angle of satellite, the greater the impact of the propagation of the signal. So during navigation process, satellite elevation angle which is less than 10 degrees should be discarded to weak the effect of the positioning tropospheric delay [16].

$$\rho_i^j = R_i^j + c\delta_{t_i} + c\delta_{t_j} + c\Delta t_i^{j-Trop} + c\Delta_i^{j-Iono} \quad (18)$$

Where, δ_{t_i} is receiver clock offset, δ_{t_j} is satellites clock offset. Δt_i^{j-Trop} and $c\Delta_i^{j-Iono}$ are pseudo range delays of ionosphere and troposphere, which can be given by Klobuchar model and Hopfield model.

2.4.3 Analysis of the impact of tropospheric delay on satellite selection algorithm.

To improve the accuracy of position, different weights are assigned accord with different navigation signals, when information is fused in multimode satellite navigation system. The smaller elevation angle is, the greater atmospheric error is made. This is harmful to improving accuracy, thus these satellites should be given lower weight. Assessing the weight with satellite elevation angle, the stochastic model can be described as [17]:

$$\sigma_i^2 = \frac{\delta_j^2}{\sin^2(\mathrm{E})} \quad (19)$$

Where E is the elevation angle of satellite j, δ_j^2 is the accuracy of zenith direction in each navigation system.

3. Simulation

With Real-time road testing and recording the BD2/GPS signals sources, the NMEA data and ephemeris data can be gotten. Then by importing these data into simulating model, we can get coordinates and elevations of receiver. Finally, comparing them to the real position, we can analyze the errors accordingly.

As is shown in Table1, in BD2 system, the message recorded by signal analyzer MP-900, include coordinate information, BD geodetic coordinate location information, GPS location information, GPS Geodetic location information, BD accuracy factor and visible GPS satellite status.

Table 1: Description of test position data(L1)

$BDGGA,162053.00,4000.000058,N,11559.999656,E,1,20,0.6,109.4,M,-7.9,M,,,1.0*65
$BDGLL,4000.000058,N,11559.999656,E,162053.00,A,0*09
$GPGGA,162051.00,4000.000058,N,11559.999656,E,1,20,0.6,109.4,M,-7.9,M,,,1.0*67
$GPGLL,4000.000058,N,11559.999656,E,162051.00,A,0*0B
$BDGSA,A,3,01,03,07,08,09,04,05,02,10,11,12,,1.2,0.6,1.0,0.6*26
$GPGSV,3,1,9,01,35,089,41,32,10,319,41,06,60,319,40,11,58,247,40*48
....

Table2 can be obtained from the second and third sub-frame in the navigation message satellite ephemeris data.

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For the special satellite, the satellite ephemeris should contain the flowing information: Satellite Serial Number, Satellite reference time(s), Satellite orbital eccentricity, Tilt angle at reference time satellite, Orbital perigee and RAAN rate of change. Using Klobuchar model, we can calculate pseudo range delay error.

Table 2: Description of test almanac data

1.2.949120000e+0052.656033380e+0073.612995148e-0039.551630981e-001-5.632679332e-001 -1.198179435e+000 -3.060399904e+000 -7.988904198e-009
2 2.949120000e+005 2.655971979e+007 1.284646988e-002 9.539706678e-001 1.487081273e+000 -2.677285581e+000 -3.772203317e-001 -7.977475151e-009
4 2.949120000e+005 2.655858741e+007 3.174781799e-003 9.632344736e-001 -2.667212465e+000 -1.251523468e+000 2.028748390e+000 -8.011762293e-009

We selected 20 sampling points and draft their location. Figure 2 describes the distribution of visible satellites in 20 sampling points. Figure3 describes ionosphere correction circumstances of 5th at 20 sampling time points .At first ionosphere correction is about 4.45 meters, only 4.4 meters (minimum value at this fall) when it reaches the fourth time, and then it gradually increases in the first 20 time points to reach a maximum of 5.8 meters.

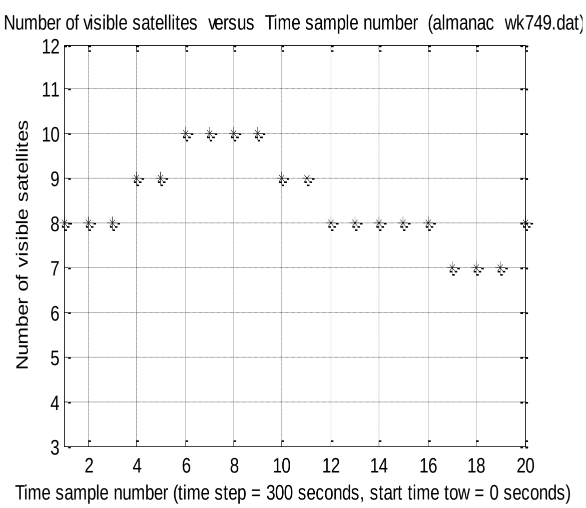

Fig. 2. The distribution of visible satellites

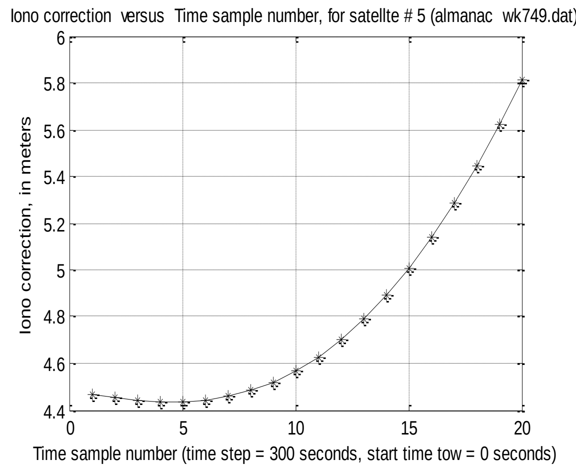

Fig. 3. Ionospheric correction of the 5th satellite

We use the marked position of the receiver and the measurement data to evaluate. Fig.5 shows ionospheric delay error relative to the real data,when use the Klobuchar model [14] and not use. When no correction model is corrected, the error is large and the ionospheric delay error in a different time delay fluctuate largly; thus it will affect the positioning accuracy of the system. On the contrary, it will improve the positioning accuracy.

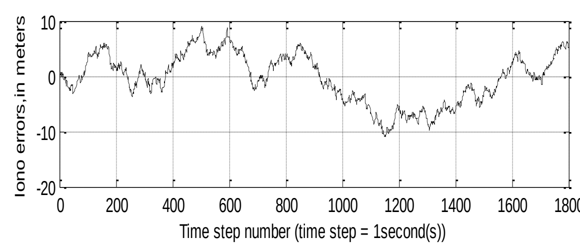

Fig. 4. The ionospheric delay error when not use Klobuchar model.

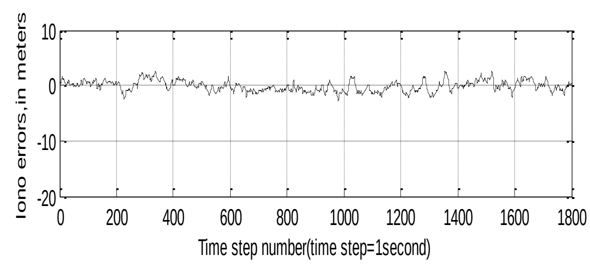

Fig. 5. The ionosphere delay error whihout Klobuchar model.

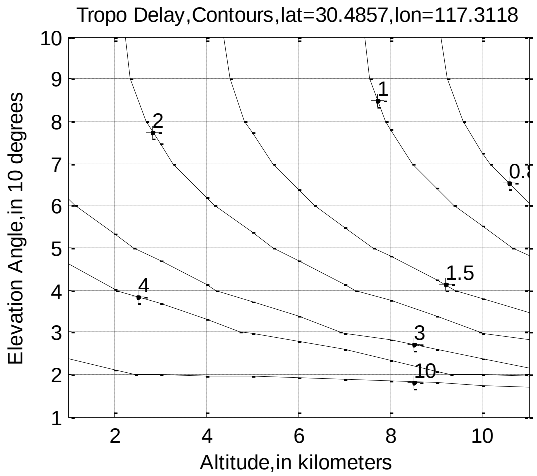

Fig. 6. Delay error of Troposphere under the special latitude and longitude

Fig.6 illustrates the relationship between the elevation angle of satellite and Tropospheric delay .When the elevation is 10 kilometers, the elevation angle ranges from 10 degrees to 20 degrees, the signal which is from combined satellite system will spend long time passing through troposphere [15], thus will affect the GPS signal. We can see that the principal effects of tropospheric delay error are elevation accuracy, the greater the height is, and the greater the error is. However, the elevation angle has not less than 10 degrees. When the base line is 30 km, the elevation error caused by troposphere is between 3 meters and 8 meters. This value will increase several times when the elevation angle decline down to less than 10 degrees.

4. Conclusions

Ionosphric delay and tropospheric delay are the chief error sources of BD2/GPS combined system. Some models such as Klobuchar model and Hopfield model are adopted to restrain those errors in GPS system, and these methods can also be introduced to BD2/GPS combined system. The experimental result shows that with modeling correction, the ionosphric delay and tropospheric delay become relatively small, and further improvement in positioning accuracy is possible for BD2/GPS combined system.

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