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An Algorithm for Inter-Satellite Autonomous Time Synchronization and Ranging in the Beidou Navigation Satellite System

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Abstract

Aiming at the requirement of the autonomous time synchronization in BeiDou Navigation Satellite System (BDS), an algorithm for inter-satellite autonomous time synchronization and ranging is proposed. Based on the establishment of the inter-satellite link length model of the BDS, a series of simulation has been carried out through the use of STK (Satellite Tool Kit), which includes the simulation of the length changing rules, the length variation scale and its variation ratio. Based on these simulations, an analysis of the impact of satellite motion on the inter-satellite two-way time synchronization and range has been presented. In this algorithm, the inter-satellite clock-offset and range with minimal error are acquired by utilizing the combination of clock-offset fitting polynomial and range fitting polynomial based on the least square fitting of data generated from the inter-satellite two-way time synchronization. Empirical evaluation of the BDS simulation shows that our time synchronization error is 2ns, and ranging error is 2m under the condition of acceptable simulation error. With the application of the algorithm to the inter-satellite autonomous time synchronization and ranging, the high-accuracy measurement of inter-satellite clock-offset and range of BDS can be reached.

Keywords: *Satellite navigation, BeiDou Navigation Satellite System (BDS), Autonomous time synchronization, Inter-satellite ranging*

1. Introduction

The requirement of high-precision time frequency for aerospace applications, such as BeiDou satellite navigation, has become increasingly important with the rapid development of national space science and technology. In general, current time base correctors are ground-based; hence, inter-constellation satellites of the navigation system must be time synchronized with ground stations [1-3]. However, ground stations have restricted visibility regions because of the limited home range and thus cannot completely cover the orbit and range of satellites. The accuracy of time synchronization is also affected by atmospheric refraction, interruption, and recession. The efficiency of satellite navigation declines when ground stations are offline. Considering the significance of autonomous time synchronization in implementing constellation autonomous navigation, researchers have focused on developing algorithms for inter-constellation autonomous time synchronization. Shui[4] developed a Kalman filtering algorithm for navigation

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constellation satellite time synchronization, established system state equations on the basis of the frequency stability Allan variance of on-board atomic satellite clocks, and used the pseudo-range differences between two satellites as the basic measurements to obtain system measurement equations. Ref. [5] discussed a conditional estimation-based auto-timing calculation method that infers pseudo-range measurements with inter-satellite clock differences from inter-satellite two-way ranging results. Ref. [6] presented analyses and techniques of motion influence on inter-satellite two-way time-comparison measurement for satellite formation flight. Huang [7] also introduced a time synchronization method for inter-satellite autonomous dynamic two-way synchronization and provided a detailed explanation of the synchronization error.

Two-way time synchronization is a highly accurate method [1]. With this algorithm, a mutual time synchronizing signal is established, propagation latency is eliminated based on the path symmetry, and the exact position information of both sides is unnecessary. Synchronized satellites should remain relatively motionless to others to ensure the path latencies are approximately the same. The exact position of satellites cannot be obtained in advance because of the principle of autonomous time synchronization for navigation constellation. Therefore, the two-way time synchronization algorithm may be used in the inter-satellite time synchronization of navigation constellation to implement constellation autonomous time synchronization without the participation of ground stations. In this paper, the satellite mobility pattern for BDS is simulated to analyze the adverse effect of satellite motion on the accuracy of inter-satellite two-way time synchronization and ranging. A new algorithm for eliminating the negative effect of satellite motion on the accuracy of inter-satellite time synchronization and ranging is proposed, and this algorithm can be applied for inter-satellite high-accuracy time synchronization and ranging in BDS.

2. Theory of Inter-satellite Autonomous Time Synchronization and Ranging

The theory of inter-satellite autonomous time synchronization and ranging is shown in Figure 1[7]. The graph shows that the wireless transmitter and receiver are both installed on satellites A and B. The satellites send and receive time synchronizing and ranging signals to and from each other concurrently. The process can be described with the following formula [8].

$$T_1 = \Delta t + t_2 + \tau_{BA} + r_1 + \delta_1 \tag{1}$$

$$T_2 = -\Delta t + t_1 + \tau_{AB} + r_2 + \delta_2 \tag{2}$$

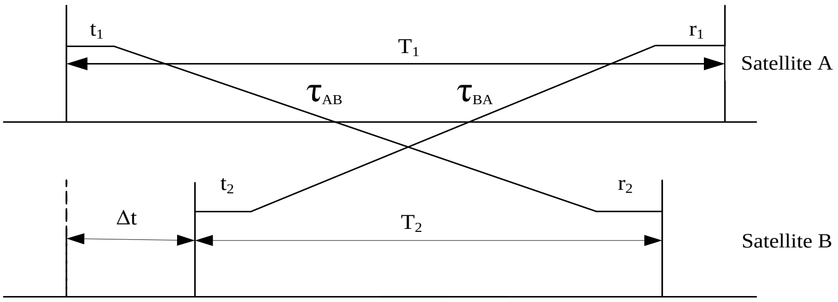

Figure 1. Theory of Inter-Satellite Autonomous Time Synchronization and Ranging

Where Δt denotes the clock-offset between satellites A and B, T_1 denotes the time difference between timing signals from satellite A to B and timing signals from satellite B to A, t_2 denotes the delay of transmitted signals of satellite B, τ_{BA} denotes the propagation delay from satellite B to A, r_1 denotes the time delay for received signals of satellite A, δ_1

denotes other time delays, T_2 denotes the time difference between timing signals from satellite B to A and timing signals from satellite A to B, t_1 denotes the delay of transmitted signals of satellite A, τ_{AB} denotes the propagation delay from satellite A to B, r_2 denotes the time delay of received signals of satellite B, and δ_2 denotes other time delays. T_1 and T_2 can be measured at satellites A and B separately, t_1 and t_2 are known values calibrated by satellite frequencies in advance, and r_1 and r_2 are known values calibrated by satellite-transmitted signal frequencies in advance. When the two satellites use similar signal frequencies for time synchronization and ranging in a symmetric link with approximate similar propagation delay, we can infer that $\tau_{AB}=\tau_{BA}$. The inter-satellite range ρ and clock-offset Δt of satellites A and B can be calculated without counting other time delays δ_1 and δ_2. If the clock-offset Δt remains the same during inter-satellite time synchronization and ranging, then the time delay of the transmitter and receiver in addition to other time delays can be eliminated. We obtain the following formulas by rearranging and simplifying Formulas (1) and (2).

$$\Delta t = \frac{T_1 - T_2}{2} \tag{3}$$

$$\tau_{AB}(\tau_{BA}) = \frac{(T_1 + T_2)}{2} \tag{4}$$

Formula (3) is the derivation of the clock-offset Δt. The inter-satellite range ρ can be obtained by using Formula (4) multiplying the light speed c.

$$\rho = c \cdot \tau_{AB} = c \cdot \frac{T_1 + T_2}{2} \tag{5}$$

3. Constellation Parameters and Inter-satellite Link Length Model of BDS

3.1 Constellation Parameters of BDS

In consideration of the orbital altitude, the BDS constellation has adopted the following three types of satellite orbits to implement the sustained global covering and regional enhancement: the Geosynchronous Earth Orbit (GEO), the Inclined Geo Synchronous Orbit (GSO), and the medium earth orbit (MEO). The space segment consists of a constellation of 35 satellites: five GEOs located at 58.75°E (GEO01 satellite), 80°E (GEO02 satellite), 110.5°E (GEO03 satellite), 140°E (GEO04 satellite), and 160°E (GEO05 satellite), as well as 30 non-GEOs that are formed by 27 MEO satellites and three IGSO satellites. The MEO satellites are evenly distributed in three orbital planes, with an orbit height of 21500 m and an inclination of 55°. The IGSO satellites are evenly distributed in three inkling synchronization planes, with an orbit height of 36000 km and an inclination of 55°, and the track of sub-satellite points of these three IGSO satellites is overlapped at 118°E, with a phase difference of 120°[9].

3.2 Inter-Satellite Link Length Model

The length model of an inter-satellite link in Figure 2, where the satellites move in a circular orbit, shows that satellites A and C are a pair of satellites in a synchronized orbit. Satellites A and S have different orbit heights, satellite B is the projection of satellite S on the plane of satellite A[10], d_{AC} is the inner-orbit length of the inter-satellite link, and d_{AS} is the inter-orbit length of the inter-satellite link.

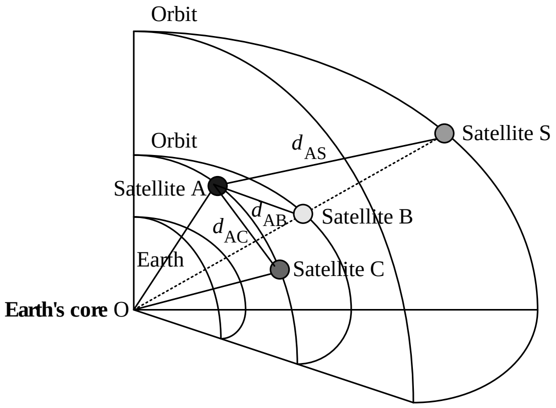

Figure 2. Inter-Satellite Length Model

The sections of satellites A, B, and C on the celestial sphere at a certain point in time are shown in Figure 3[11], where Φ_{AS} is the elevation angle of the inter-satellite link from satellite A to S, and Φ_{SA} is the elevation angle of the inter-satellite link from satellite S to A. In addition, ξ is the geocentric angle between satellites A and S, which meets $\xi = \angle AOB = \angle AOS$.

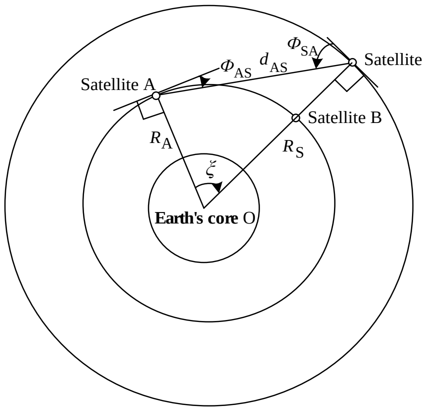

Figure 3. Sketch Map of the Elevation Angle of the Inter-satellite Link

If the orbit radii of satellites A and S are R_A and R_S, respectively, then the calculation formulas for the inter-satellite link length on different planes can be concluded from Figures 2 and Figures 3.

$$d_{AS} = \sqrt{{R_A}^2 + {R_S}^2 - 2R_A \cdot R_S \cos\xi} \tag{6}$$

Formula (6) indicates that the length of the inter-satellite link changes with ξ, which can be expressed by the longitude and latitude of satellites A and B on the celestial sphere (λ_A, φ_A) and (λ_B, φ_B).

$$\xi = \arccos[\sin\varphi_A \cdot \sin\varphi_B + \cos\varphi_A \cdot \cos\varphi_B \cdot \cos(\lambda_A - \lambda_B)] \tag{7}$$

In the ECI coordinate system, the longitude λ and latitude φ of the satellite on the celestial sphere can be calculated from the following formula.

$$\begin{cases} \lambda=\Omega_0+\arctan(\cos i\cdot\tan\theta)+\begin{cases} -180°(-180°\leq\theta<-90°) \\ 0°(-90°\leq\theta\leq 90°) \\ 180°(90°<\theta\leq 180°) \end{cases} \\ \varphi=\arcsin(\sin i\cdot\sin\theta) \end{cases} \quad (8)$$

In Formula (8), the angular distance between the satellite and its ascending node is denoted as $\theta=\omega\cdot t+\gamma_0$, where γ_0 is the original satellite phase, ω is the angular speed of the satellite in the geosynchronous orbit, and Ω_0 is the longitude of the ascending node. Orbit inclination is denoted as i, and the satellite motion duration t is calculated since the satellite crossing the ascending node. After importing Formulas (7) and (8) into Formula (6), regulations for the changes in the length of the inter-satellite link with time can be obtained. The time derivative of Formula (6) is the change ratio of the inter-satellite link length of different planes.

$$\frac{\partial d_{AS}}{\partial t}=\frac{R_A\cdot R_S}{\sqrt{R_A{}^2+R_S{}^2-2R_A\cdot R_S\cos\xi}}.\sin\xi.\frac{\partial\xi}{\partial t} \quad (9)$$

3.3 Simulation Results for the Length of the BDS Inter-Satellite Link

STK-based simulation tests on the length change range and ratio of the inter-satellite link among the GEO, IGSO, and MEO satellites of BDS are conducted using the model of the inter-satellite link, and the results are shown in Table 1.

Table 1. Comparison of Length and Change Ratio of the Inter-satellite Link in BDS

Link Type	Link Length (km)		Change Ratio of Link Length (km/s)	
	Maximum Value	Minimum Value	Maximum Value	Minimum Value
GEO-MEO	68827.889068	14288.193774	2.808950	−2.808950
IGSO-MEO	68827.432952	14288.122039	4.241172	−4.240383
GEO-IGSO	53319.089648	4234.633141	2.547426	−2.547275

Simulation results for the length change range and ratio of the inter-satellite link between an IGSO satellite and a MEO satellite of BDS at time points 3 May 2013 00:00:00.000-10 May 2013 00:00:00.000 are shown in Figure 4.

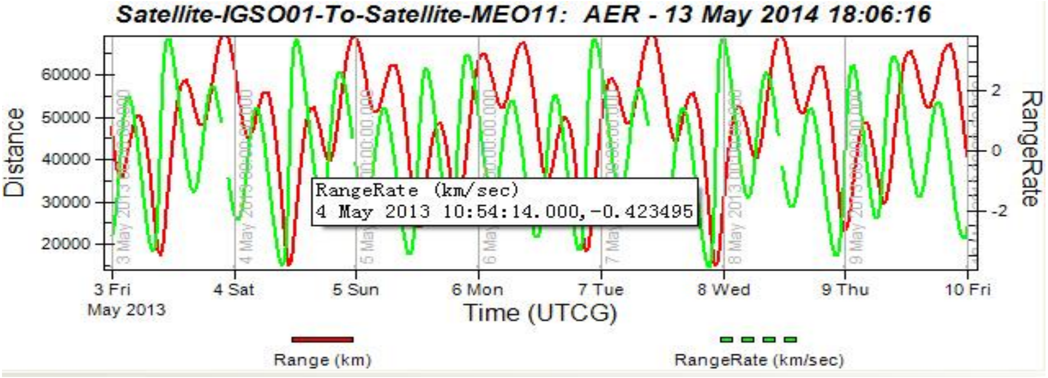

Figure 4. Inter-satellite Link Length and Change Ratio of IGSO01-MEO11 in BDS

We can infer from Table 1 and Figure 4 that the length change range and ratio of the inter-satellite link between satellites in different planes considerably vary during the simulation interval, and the maximum change ratio is 4.241172 km/s. Thus, the effects of satellite motion on two-way synchronization and ranging must be eliminated to improve the accuracy of time synchronization and ranging and thus implement the autonomous time synchronization and ranging between satellites of the constellation in different planes.

4. Inter-satellite Autonomous Time Synchronization and Ranging Algorithm by the Fitting Method

4.1 Effect of Satellite Motion on Inter-Satellite Two-Way Time Synchronization and Ranging

Figure 5 presents a case example of inter-satellite two-way time synchronization and ranging between two moving satellites of a constellation. In this example, satellites A and B first approach each other and then move in opposite directions. We suppose that the speed of satellite A is v_A, and the speed of satellite B is v_B, which satisfies $v_B<v_A$. The effects of satellite motion on inter-satellite two-way time synchronization and ranging are analyzed on the basis of the above assumption.

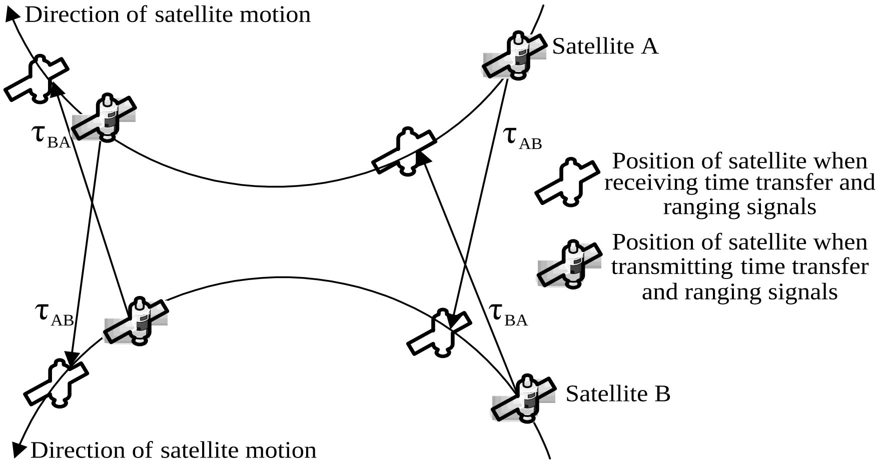

Figure 5. Inter-satellite Link Length and Change Ratio of IGSO01-MEO11 in BDS

As shown in Figure 5, $v_B < v_A$ and $\tau_{BA}<\tau_{AB}$ when satellite A approaches satellite B. Thus, the time difference between satellites A and B, T_1 and T_2, which are calculated separately using Formulas (1) and (2), would be smaller than the still values. The actual inter-satellite clock-offset yields to the theoretical calculation Δt based on Formula (3), and the amendatory value $(\tau_{AB}-\tau_{BA})/2$ is greater than 0. The actual inter-satellite range ρ yields to the theoretical calculation based on Formula (5). When the two satellites separate, $v_B<v_A$ and $\tau_{BA}<\tau_{AB}$, which indicate that the clock-offset values of satellites A and B, T_1 and T_2, are both smaller than the still values. The theoretical inter-satellite clock-offset Δt yields to the actual value, and the amendatory value $(\tau_{AB}-\tau_{BA})/2$ is smaller than 0. The inter-satellite range ρ based on Formula (5) is less than the actual value.

4.2. Inter-Satellite Autonomous Time Synchronization and Ranging Algorithm based on the Fitting Method

The above simulation tests and error analysis indicates that the differences between the inter-satellite clock-offset and range based on the two-way time synchronization algorithm and the actual values change from negative to positive during the meeting and separation of satellites A and B. The minimum value occurs when the relative velocity of the two satellites reaches its minimum because the satellite motion currently having the smallest effects on the algorithm and the delay of constellation two-way time synchronization is almost the same as that of the ranging signal propagation. During this time interval, the inter-satellite distance and clock-offset fitting polynomial are determined by fitting the two types of inter-satellite distance and clock-offset data to the least square fitting model [12].

$$\begin{cases} \rho = f_1(t) \\ \Delta t = f_2(t) \end{cases} \tag{10}$$

When the relative velocity of the two satellites reaches its minimum, the time derivative of the distance fitting polynomial is also the minimum point t_2 of the distance function, and the minimum error between the fitted and actual values $\rho_{\min}$ and $\Delta t_{\min}$ is calculated as

$$\begin{cases} \rho_{\min} = f_1(t_2) \\ \Delta t_{\min} = f_2(t_2) \end{cases} \tag{11}$$

5. Analysis of Simulation Results

During inter-satellite time synchronization and ranging, the clock-offset between satellites A and B remains relatively constant at 1us. Ignoring the delays of the transmitter and receiver, we explore multiply tests on time synchronization and ranging at the same time interval with different lengths and time intervals but at the same duration, with the GEO and IGSO satellites of BDS denoted as satellite A and the MEO satellite of BDS denoted as satellite B. Using the STK tool, we perform two simulation tests on the GEO and MEO satellites within the same interval. The former keeps 6 minutes, and the latter keeps 8 minutes. The test data are obtained from the simulation on the IGSO and MEO satellites at different intervals but at the same duration of 8 minutes. The above time intervals are distributed symmetrically relative to the time point at which the minimum inter-satellite distance appears.

5.1. Simulation Results for Inter-Satellite Autonomous Time Synchronization

The time-varying polynomials of range and clock-offset among the GEO, IGSO (satellite A), and MEO satellites (satellite B) are obtained on the basis of the above data fitting. The time point at which the minimum inter-satellite range appears can be calculated by applying the inter-satellite range polynomial, and then the current inter-satellite clock-offset can be conducted by substituting the preceding time point. The correctness of our algorithm can be validated by calculating the difference between the hypothetical inter-satellite clock-offset and the simulated one. The comparison results are shown in Table 2. The range calculating method uses a second-order polynomial fit, whereas the clock-offset uses a first-degree polynomial.

Table 2. Least Square Fitting Results of the Inter-satellite Clock-offset (suppose inter-satellite clock-offset = 1000ns)

Time synchronization satellite	GEO-MEO		IGSO-MEO	
Time interval for inter-satellite synchronization	9:14:19.00-9:20:19.00 (4 May 2013, 6 min)	9:13:19.00-9:21:19.00 (4 May 2013, 8 min)	9:32:26.00-9:40:26.00 (3 May 2013, 8 min)	21:12:31.00-21:20:31.00 (6 May 2013, 8 min)
Inter-satellite range fitting polynomial	$\rho=0.00048856036t^2$ $-0.17500638249t$ $+14806.75847392750$	$\rho=0.00048833919t^2$ $-0.23367823075t$ $+14819.04310802786$	$\rho=0.00072817496t^2$ $-0.34880790595t$ $+17567.19403271861$	$\rho=0.00069951624t^2$ $-0.33493571701t$ $+18206.27346205789$
Time point corresponding to the minimum	179.1041576126913	894.5529194897511	239.5083096510539	239.4052480578224

inter-satellite range ρ_{min}(s)				
Clock-offset polynomial	$\Delta t=-2.587107684084t+1466.537190645435$	$\Delta t=-0.78531048318t+1706.51268703129$	$\Delta t=-0.434922805805t+1104.814567597937$	$\Delta t=-0.450800223084t+1108.340740765060$
Hypothetical inter-satellite clock-offset(*ns*)	1000	1000	1000	1000
Fitted inter-satellite clock-offset $\Delta t_{\min}$(*ns*)	1003.175448234288	1002.083728748065	1000.646941550877	1000.416801533016
Differences between two clock-offsets(*ns*)	3.175448234288	2.083728748065	0.646941550877	0.416801533016

As shown in Table 2, the clock-offset polynomial exhibits an enhanced performance with a small fitting error and a high time synchronization accuracy when the time interval for synchronization and the arising time of the minimum inter-satellite distance is symmetrical. The minimum simulation error of the algorithm is 0.416801533016ns. The average value of the four times synchronization shows that the time synchronization accuracy is under 2ns, which indicates that the clock-offset based on the autonomous time synchronization algorithm is close to the actual one. Thus, the accuracy of the algorithm is acceptable.

5.2. Simulation Results of Inter-Satellite Autonomous Ranging

Following the example of the inter-satellite autonomous time synchronization method, we can calculate the inter-satellite range with minimum error by substituting the time point at which the minimum range appears to the inter-satellite fitting polynomial. The correctness of the inter-satellite ranging algorithm can be evaluated by comparing the difference between the fitted value and the STK simulation result. Table 3 shows the comparison results.

Table 3. Least square fitting results of inter-satellite ranging

Inter-satellite ranging satellite	GEO-MEO		IGSO-MEO	
Time interval for inter-satellite ranging	9:14:19.00-9:20:19.00 (4 May 2013, 6 min)	9:13:19.00-9:21:19.00 (4 May 2013, 8 min)	9:32:26.00-9:40:26.00 (3 May 2013, 8 min)	21:12:31.00-21:20:31.00 (6 May 2013, 8 min)
Inter-satellite range fitting polynomial	$\rho=0.00048856036t^2-0.17500638249t+14806.75847392750$	$\rho=0.00048833919t^2-0.23367823075t+14819.04310802786$	$\rho=0.00072817496t^2-0.34880790595t+17567.19403271861$	$\rho=0.00069951624t^2-0.33493571701t+18206.27346205789$
Time point corresponding to the minimum inter-satellite range $\rho_{min}(s)$	179.1041576126913	894.5529194897511	239.5083096510539	239.4052480578224
Fitted value of inter-satellite range (*m*)	14791086.28865635	14791088.40121514	17525422.83694266	18166180.77795916
STK simulation results of inter-satellite range (*m*)	14791086.401	14791086.401	17525420.608	18166177.299
Difference between two	−0.1123436504713027	2.000215139560	2.228942659713	3.478959162749

ranges (m)

As shown in Table 3, the fitted range value yields the highest accuracy with a minimum error of -0.1123436504713027m when the distance ranging time interval and the arising time of the minimum inter-satellite distance is symmetrical. The average value of the four times ranging shows that the accuracy is under 2m, which means that the inter-satellite range based on the autonomous time synchronization algorithm is close to the STK simulation result. Thus, the accuracy of the algorithm is acceptable.

6. Conclusions

Considering the requirement for autonomous time synchronization in BDS, this study proposes an algorithm based on the fitting method for inter-satellite autonomous time synchronization and ranging. The effects of satellite motion on the accuracy of the inter-satellite two-way time synchronization and ranging algorithm are explored by simulating the change law of inter-satellite range in different planes of the satellite constellation. The method uses a second-order polynomial fit, and the clock-offset uses a first-degree polynomial. When the time interval for synchronization, ranging and the arising time of the minimum inter-satellite distance are symmetrical, the synchronization and ranging accuracy are under 2ns and 2m, respectively, which are within the range of acceptable simulation error. Applications of the algorithm for practical inter-satellite autonomous time synchronization and ranging, the effects of the satellite moving direction and the Sagnac effect on the algorithm can be crippled, the accuracy of the time synchronization and ranging can be increased with better data processing method, which satisfy the requirement for high-accuracy autonomous time synchronization and ranging in BDS.

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