An inter-satellite dynamic ranging algorithm based on two-way time synchronization

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Abstract

Inter-satellite precise ranging is the foundation for all aerospace application systems in realizing autonomous navigation. To acquire a high-accuracy inter-satellite range, this study investigates an inter-satellite dynamic ranging algorithm. Referring to the simulation of inter-satellite range variation rules in constellation, this study analyzes the negative impact of satellite motion on inter-satellite ranging and proposes corresponding improved methods to eliminate the major error caused by satellite motion. This algorithm solves the minimal error in inter-satellite range using a combination of inter-satellite range fitting polynomial and inter-satellite clock-offset fitting polynomial, both of which are generated by two-way time synchronization data. Simulation calculation results show that the accuracies of inter-satellite ranging can be controlled within 3m provided that simulation error is considered. The algorithm can be used to improve the accuracy of inter-satellite dynamic ranging of various aerospace application systems.

Keywords: aerospace application systems, autonomous navigation; inter-satellite communication, two-way time synchronization, inter-satellite dynamic ranging

1 Introduction

With the rapid development of aerospace technology, constellation autonomous navigation and autonomous ranging have become a key direction in aerospace technology development [1-5]. As the key technology in constellation autonomous navigation, inter-satellite communication links establishment and maintenance technologies and inter-satellite ranging technologies has been studied widely. Long-term satellite ephemeris and clock reference are revised constantly from the ground station through the data exchange in inter-satellite ranging and the filtering process by satellite-borne processors. Furthermore, navigation messages are autonomously generated, and basic constellation configuration is thus maintained. As a result, the application demand for constellation autonomous navigation is met [5]. Choosing the appropriate inter-satellite ranging method and obtaining a precise inter-satellite range are the key issues that must be addressed to realize constellation autonomous navigation.

Many studies have investigated constellation autonomous navigation and inter-satellite ranging [5-8]. Reference [5] takes advantage of time synchronization and ephemeris in satellite constellation for updating the Kalman filter to process two-way inter-satellite ranging data. This method is able to realize precise time synchronization for satellite constellation and high-accuracy satellite orbit determination. The maximum user ranging error after filter convergence of satellite radial orbit is less than 6 m. Reference [6] analyzes the constellation autonomous navigation method based on inter-satellite ranging information and deduces the location of inter-satellite ranging information as well as the model and condition of time decoupling. The work puts forward the solving process that involves updating the location and time consecutively. The work also deduces a distributed Kalman filtering algorithm based on the characteristics of state and measurement equations. This algorithm is applicable in solving constellation autonomous navigation. Reference [7] proposes an autonomous orbit determination algorithm using an improved Kalman filtering fusion dynamic information and inter-satellite ranging information. This algorithm could achieve on-time revision of integral initial value. Reference [8] proposes the use of little ground emission source to provide a ground base. The method combines inter-satellite ranging and ground emission source information to conduct and improve the accuracy of orbit determination for whole satellite constellation. The

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aforementioned studies focus on improving the accuracy of orbit determination and realizing autonomous navigation through inter-satellite ranging data. However, research on how to obtain high-accuracy inter-satellite range is rare. Referring to reference 9 and by simulating the changing characteristics of moving satellites, this study proposes a dynamic measurement algorithm for high-accuracy inter-satellite range gained from an inter-satellite pseudo-range fitting polynomial. This algorithm is capable of realizing high-accuracy inter-satellite ranging while achieving high-accuracy time synchronization.

2 Principle of two-way time synchronization for inter-satellite ranging

The principle of two-way time synchronization for inter-satellite ranging is shown in Figure 1 [9]. A radio transmitter and receiver are installed on satellites A and B. The following equations can be obtained when satellite A and B are sending time synchronization signal to each other at the same time and receiving each other's signal:

$$T_1 = \Delta t + t_2 + \tau_{BA} + r_1 + \delta_1 , \quad (1)$$

$$T_2 = -\Delta t + t_1 + \tau_{AB} + r_2 + \delta_2 . \quad (2)$$

In the previous equations, Δt is the clock correction of satellites A and B. T_1 is the time difference between the transmission of timing signal by satellite A and its receipt of timing signal transmitted by satellite B. t_2 is the transmission delay of satellite B, τ_{BA} is the propagation delay from satellite B to satellite A, r_1 is the receiving delay of satellite A, δ_1 is the other delay [10], T_2 is the time difference between the transmission of timing signal by satellite B and its receipt of timing signal transmitted by satellite A, t_1 is the transmission delay of satellite A, τ_{AB} is the propagation delay from satellite A to satellite B, r_2 is the receiving delay of satellite B, and δ_2 is the other delay.

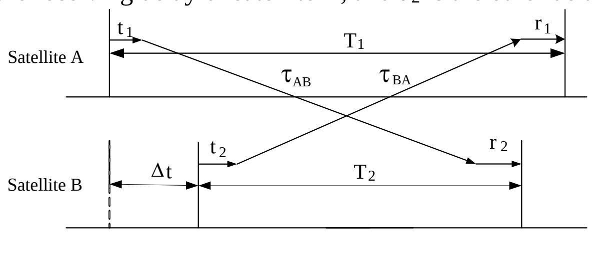


FIGURE 1 Schematic of two-way time synchronization for inter-satellite ranging

To determine the inter-satellite range and clock offset of the two satellites, Equations (1) and (2) can be arranged such that the following results are obtained:

$$(\tau_{BA} + \tau_{AB}) = (T_1 + T_2) - (t_1 + t_2) - (r_1 + r_2) - (\delta_1 + \delta_2) , \quad (3)$$

$$\Delta t = \frac{T_1 - T_2}{2} + \frac{t_1 - t_2}{2} + \frac{r_2 - r_1}{2} + \frac{\tau_{AB} - \tau_{BA}}{2} + \frac{\delta_2 - \delta_1}{2} . \quad (4)$$

In the previous equation, T_1 and T_2 can be obtained from the measurement of satellites A and B. t_1, t_2, r_1, and r_2 can be pre-calibrated according to the transmission frequency of satellite signal. When satellites A and B have similar timing signal frequencies, linking is symmetrical, and transmission delay is approximately equal. These conditions indicate that $\tau_{AB}=\tau_{BA}$, and other delay impacts are ignored. Finally, the inter-satellite range and clock offset of the two satellites can be obtained.

Assuming the clock correction Δt of two satellites is kept the same in the time synchronization process, and the impacts of receiving and transmitting equipment delay and other delays are ignored, Equations (3) and (4) can be simplified as:

$$\tau_{AB}(\tau_{BA}) = \frac{(T_1 + T_2)}{2} , \quad (5)$$

$$\Delta t = \frac{T_1 - T_2}{2} . \quad (6)$$

Equation (5) involves the multiple speed of light c, thus indicating that the two-way time synchronization results in the following inter-satellite range formula:

$$\rho = c\tau_{AB} = c\frac{T_1 + T_2}{2} . \quad (7)$$

3 Analysis of impact of satellite motion on the accuracy of two-way inter-satellite ranging

To analyze the impact of satellite motion on the accuracy of inter-satellite ranging, the rules on the variation of moving satellites A and B in a certain constellation for inter-satellite ranging are simulated using the Satellite Tool Kit (STK), a satellite simulation tool software. The simulation results are shown in Figure 2.

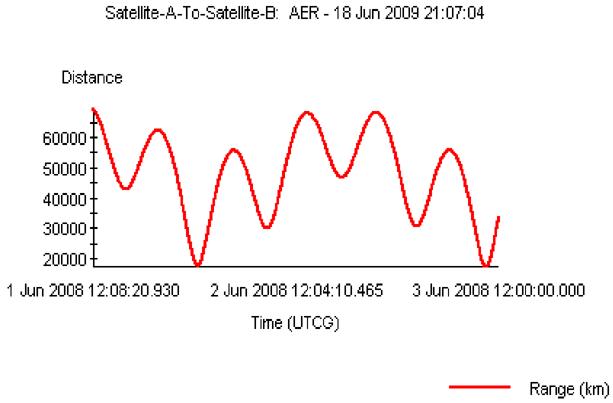


FIGURE 2 Simulation of inter-satellite range variation between satellites A and B in a constellation

As shown in Figure 2, the rules on the variation in inter-satellite range among mobile satellites in a constellation are as follows: with the moving of satellites. The phenomenon of inter-satellite range shifting from long to short and back to long occurs several times; this condition leads to regular changes in the transmission delay of the two-way inter-satellite time synchronization signal. Therefore, $\tau_{AB}=\tau_{BA}$ cannot be met normally if the two-way time synchronization algorithm is applied to solve inter-satellite ranging. Hence, the inter-satellite range acquired by Equation (7) is not equal to an actual one.

Next, a situation involving two-way ranging between GEO and MEO satellites is considered. The ranging scheme is shown in Figure 3 [11].

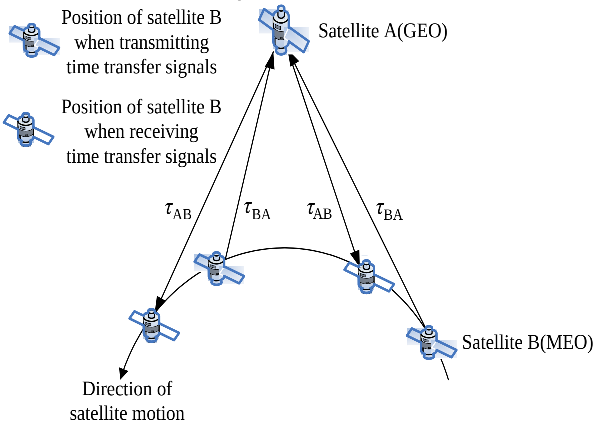


FIGURE 3 Scheme of variation of inter-satellite ranging results following inter-satellite two-way time synchronization signals propagation delay

Satellite B first moves toward satellite A then moves away. The impact of the motions of the MEO satellite on the propagation delay of two-way time synchronization signals and ranging in this situation is analyzed. Equations (1) and (2) are simplified as:

$$\tau_{AB}(\tau_{BA}) = \frac{(T_1 + T_2)}{2}, \quad (8)$$

$$\Delta t = \frac{T_1 - T_2}{2}. \quad (9)$$

When satellite B approaches satellite A, τ_{BA} becomes greater than τ_{AB} (Figure 3). Therefore, the time difference T_2 of satellite B obtained from Equation (9) is smaller than that measured when satellite B is stationary. If Equation (7) is still adopted to calculate range, then the result is smaller than the actual inter-satellite range. When satellite B keeps away from satellite A, τ_{BA} is smaller than τ_{AB} (Figure 3). Therefore, the time difference T_2 of satellite B obtained from Equation (9) is greater than that measured when satellite B is stationary. If Equation (7) is still adopted to calculate range, then the result is greater than the actual inter-satellite range.

4 An inter-satellite dynamic ranging algorithm

Considering both situations above as well as the increase and decrease in range between satellites A and B, the inter-satellite range obtained from the two-way satellite time synchronization algorithm accordingly varies from being smaller to being greater than the actual inter-satellite range. In this variation process, a certain moment occurs when the inter-satellite range obtained by the two-way inter-satellite time synchronization method is nearest the actual inter-satellite range. At the moment when the range between satellites A and B is the smallest, the propagation delays of the two-way time synchronization signals of the satellites are closest to each other. Thus, the range obtained at this moment with two-way time synchronization bears the least difference from the inter-satellite range.

According to this analysis, the pseudo-range sequence and the clock offset sequence between satellites A and B obtained by two-way time synchronization ranging in this variation process can be expressed by the pseudo-range polynomial and the clock offset polynomial, respectively. Then, the corresponding time for the minimum inter-satellite pseudo-range can be acquired from the pseudo-range polynomial. Substituting this time in the pseudo-range polynomial obtains the inter-satellite range approximate to the actual one. This method is an inter-satellite dynamic ranging algorithm that considers the impact of satellite motion on two-way time synchronization ranging. Setting the inter-satellite pseudo-range polynomial after two-way time synchronization fitting as ρ and the inter-satellite clock offset polynomial as Δt yields the following polynomial:

$$\rho = f_1(t), \quad (10)$$

$$\Delta t = f_2(t). \quad (11)$$

In Equation (10), the following is set:

$$\frac{df_1(t)}{dt} = 0. \quad (12)$$

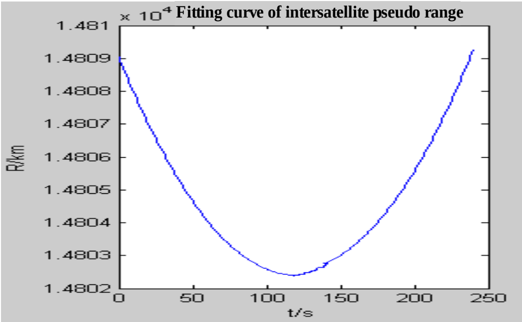
By solving Equation (12), t_3 that corresponds to minimum inter-satellite pseudo-range ρ_{min} can be obtained. Substituting ρ_{min} into pseudo-polynomial (10), the inter-satellite range approximate to the actual range can be obtained as:

$$\rho_{min} = f_1(t_3). \quad (13)$$

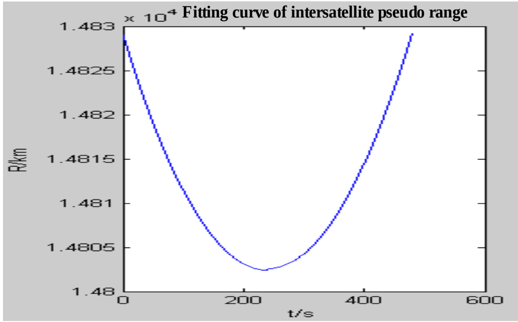
5 Simulation results and analysis

Satellite A is a GEO satellite, whereas as satellite B is an MEO satellite. Assume that the clock offset of satellites A and B is maintained at 1 μs during dynamic two-way ranging, and that the equipment delay of the receiver and transmitter as well as other delays are ignored. Aided by STK, the simulations of inter-satellite range from long to short to long are performed four times. Durations for two-way time synchronization dynamic ranging data are 4, 8, 10, and 8 minutes. The last duration (i.e., 8 minutes) at an asymmetrical time is chosen to achieve a minimum inter-satellite range. Least squares fitting are carried out for the ranging data described above. The pseudo-range polynomial between satellites A and B is then obtained. With this polynomial, the inter-satellite range minimum can be calculated. Then, this minimum value is compared with the theoretical value of the minimum inter-satellite range acquired by STK simulation. In doing so, the correctness of the algorithm can be tested.

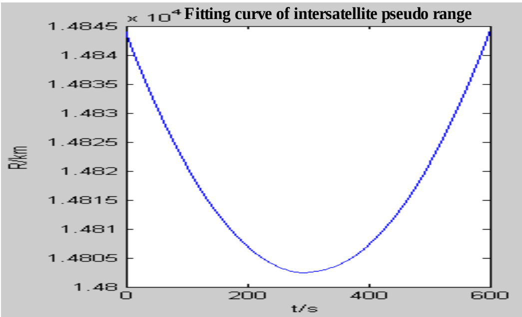
The least squares fitting curve of the pseudo-range at different ranging times is shown in Figure 4. The pseudo-range is two times fitting.



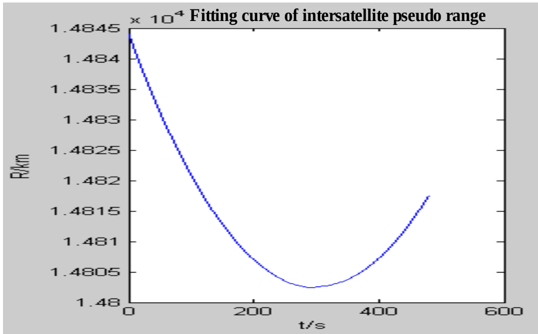
a) Results of ranging fitting for 4 minutes: 1 Jun 2008 23:35:50.000–1 Jun 2008 23:39:50.000



b) Results of ranging fitting for 8 minutes: 1 Jun 2008 23:33:50.000-1 Jun 2008 23:41:50.00



c) Results of ranging fitting for 10 minutes: 1 Jun 2008 23:32:50.000-1 Jun 2008 23:42:50.00



d) Results of ranging fitting for 8 minutes: 1 Jun 2008 23:32:50.000-1 Jun 2008 23:40:50.00

FIGURE 4 Pseudo-range fitting curve between satellites A and B

The comparison of the calculation results and the theoretical value is shown in Table 1.

TABLE 1 Comparison of the results of least squares fitting during different ranging periods (June 1, 2008, with actual clock offset of 1 μs)

Two-way time intervals for ranging	23:35:50.00-23:39:50.00	23:33:50.00-23:41:50.00	23:32:50.00-23:42:50.00	23:32:50.00-23:40:50.00
Pseudo fitting polynomial based on two-way time synchronization	ρ=0.0004627328 t^2 -0.1097262858 t +14808.9999915512	ρ=0.0004623313 t^2 -0.2212624171 t +14828.9715935283	ρ=0.0004620897 t^2 -0.2767866515 t +14843.9503933924	ρ=0.0004642350 t^2 -0.2777046942 t +14844.0118630869
Time corresponding to pseudo minimal ρ_{min}(s)	118.5633280881435	239.2898757962789	299.4944839741193	299.0992571156721
Minimum inter-satellite range determined by pseudo polynomial (km)	14802.49523448867	14802.49866317461	14802.50235286662	14802.48122818178
Theoretical value of minimum inter-satellite range by STK simulation (km)	14802.496873	14802.496873	14802.496873	14802.496873

The comparison of the inter-satellite pseudo-range fitting curve and the ranging results in Table 1 at different time show that the inter-satellite range obtained by the inter-satellite dynamic ranging algorithm based on two-way time synchronization is close to the theoretical value. Simulation results indicate that the proposed inter-satellite dynamic ranging model and the algorithm based on two-way time synchronization are correct.

As shown in Figures 4a, 4b, 4c, the fitting inter-satellite range polynomial has high accuracy, low fitting error, and high ranging accuracy when the two-way ranging duration and the time of minimum inter-satellite range are basically symmetrical. The minimal difference of the theoretical value is 1.638511330389 m. As the ranging time duration increases, the polynomial fitting error grows, and ranging accuracy decreases.

As shown in Figure 4d, the polynomial fitting accuracy is low, fitting error is large, and ranging accuracy is low when the two-way ranging duration and the time of minimum inter-satellite range are asymmetrical. The ranging result error for an eight-minute simulation can reach -15.64481822061 m.

As indicated by the above analyses, ranging duration and the duration of minimum inter-satellite range are basically symmetrical when applying the inter-satellite dynamic ranging algorithm based on two-way time synchronization in the range measurement of mobile satellites in constellation. The algorithm can reduce polynomial fitting error and increase inter-satellite ranging accuracy.

6 Conclusions

Considering the need for precise inter-satellite ranging for all kinds of aerospace application systems, this study analyzes the negative impact of satellite motion in constellation on the accuracy of two-way inter-satellite ranging. An inter-satellite dynamic ranging algorithm is also proposed. This algorithm may be used to eliminate the negative impact of satellite motion on inter-satellite ranging. The actual satellite data simulation shows that for cases in which simulation error is included, the ranging accuracy of this algorithm covers 3m when the ranging period is basically symmetrical to the moment of minimum inter-satellite range and when the pseudo-range polynomial undergoes least squares fitting. Therefore, the proposed algorithm can be used to achieve high accuracy in inter-satellite precise ranging via the mobile satellite of an aerospace application system.

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