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An Algorithm of Inter Satellite Two-Way Time Transfer Based on Mobile Satellite

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Abstract: Two-way time transfer is one of the most accurate time synchronization methods applied to spacecrafts and ground stations to carry out time transfer. As this method doesn't require the knowledge of locations of two satellites in advance and it offsets the negative influence of transmission path and other additional delays, this method has boosted the time synchronization accuracy. However, in the process of time synchronization, this method demands that the aircrafts, who conduct time synchronization, could be relatively static. So it is mainly used in GEO satellites for satellite-ground two-way time transfer. Based on the establishment of mobile satellite mutual visual model, the simulation of satellite mutual visual time on mobile satellite, including IGSO (Inclined Geo Synchronous Orbit) satellite and MEO (Medium Earth Orbit) satellite, has been conducted. The visual time and the variation range of IGSO-MEO link distance have been gained. The characteristics of the propagation delay of two-way time transfer signals between IGSO satellite and MEO satellite varying with inter satellite range were analyzed and the rule of inter satellite clock offset varying with inter satellite range obtained with this algorithm was deduced. This study presents a inter satellite dynamic two-way time transfer algorithm based on mobile satellite. The high-accuracy inter satellite clock offset is solved through the combination of inter satellite pseudo-range polynomial fitting and clock-offset polynomial fitting. Simulation results showed that with the algorithm the inter satellite time transfer error can be controlled within 1ns. The algorithm can be used high-accuracy time transfer between mobile satellites.

Keywords: Inter satellite time synchronization, mobile satellite, satellite communication, two-way time transfer

INTRODUCTION

After the space-based comprehensive information network is presented, aerospace integration is becoming a basic trend of development in the field of aerospace (Kimura *et al*., 1996; Dai and Lu, 2004; Wang, 2007). How to realize time synchronization between all spacecrafts, between spacecrafts and ground facilities and how to allow all systems to conduct cooperative work under the unified time will be major issues to be solved in the process of aerospace integration. The choice of appropriate time synchronization method and the acquisition of high-accuracy clock offset is basis of high-accuracy time synchronization (Wang *et al*., 2010; Jiao and Kou, 2011). Two-way time transfer is one of the most accurate time synchronization methods applied to spacecrafts and ground stations to carry out time transfer (Li, 2002; Zhang, 2003; Wu *et al*., 2003). This method improved the accuracy of time transfer by eliminating the impact of propagation paths and extra delay caused by atmosphere. But this method requires the spacecrafts and ground stations, on which time transfer is to be performed, to keep a relatively static state in time transfer. So it is mainly used in GEO satellites for satellite-ground two-way time transfer.

There has been some literature, in which two-way methods were used for treating two-way time transfer in motion situations. Chen *et al*. (2007) introduced a method of satellite-ground two-way time transfer for MEO satellites; An algorithm for processing data of inter satellite two-way matching measurement in formation flying satellites was deduced (Zhong and Chen, 2007) with the motions of satellites being taken into account; Celano *et al.* (2002) gave the data processing results of dynamic two-way satellite time transfer conducted with commercial satellite modem.

According to the mobile satellite mutual visual model, visual time and link distance variation range Between IGSO and MEO satellite is simulated. Rules of the variation of inter satellite distance between IGSO

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and MEO satellites have been gained. The rule of the propagation delay of two-way time transfer signals between IGSO satellite and MEO satellite varying with inter satellite range is analyzed. This study presents an algorithm of inter satellite dynamic two-way time transfer with which high-accuracy inter satellite clock offset is solved through the combination of inter satellite pseudo-range polynomial fitting and clock-offset polynomial fitting.

MOBILE SATELLITE MUTUAL VISUAL MODELING AND SIMULATION

Mobile satellite mutual visual model: For those two earth-around-rotating satellites, after the determination on locations of satellites at any time in the space, they can only achieve visibility when they are both above the same plane which is tangent to the earth surface. The extreme situation is that both of them are in the tangent plane. Therefore, the visibility function to describe that whether these two satellites can achieve visibility is gained, as shown in the Fig. 1 (Zhang and Zhang, 2001).

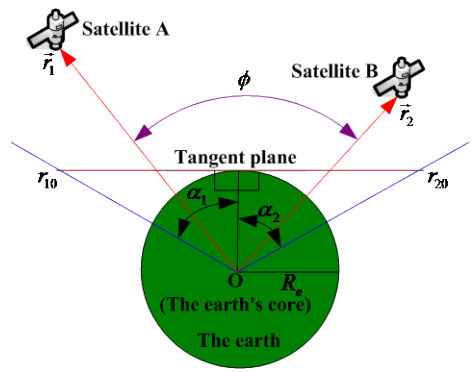


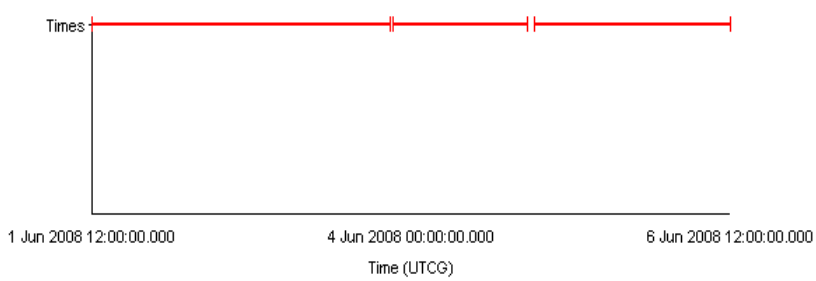
Fig. 1: Mutual visual time's calculation model of mobile satellite

The function is as follows:

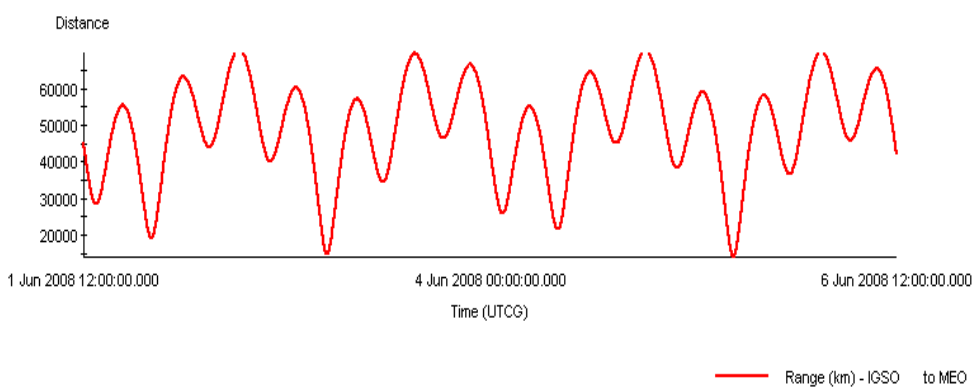
$$\psi = \alpha_1 + \alpha_2 - \phi \tag{1}$$

In formula (1), α_1, α1 and Φ are calculated as following formula:

$$\alpha_1 = \arccos(R_e / r_{10}) \tag{2}$$



(a) Visual time for IGSO satellite and MEO satellite



(b) Rules of the variation of link distance between IGSO and MEO

Fig. 2: Visual time and link distance variation range simulation of IGSO-MEO satellite

$$\alpha_2 = \arccos(R_e / r_{20}) \quad (3)$$

$$\phi = \frac{(\vec{r}_1 \cdot \vec{r}_2)}{|\vec{r}_1| \cdot |\vec{r}_2|} \quad (4)$$

When Ψ>0, the two satellites can achieve visibility. Otherwise, there is no visibility.

Visual time and link distance variation range simulation of IGSO-MEO satellite: To test the above mobile satellite mutual visible model, IGSO (the height of orbit is 35786 km, orbit inclination is 55°) was adopted as GEO satellite (satellite A) and MEO-0-01 (the height of orbit is 22116 km, orbit inclination is 55°) as MEO satellite (satellite B). The simulations of IGSO-MEO satellite have been done with the help of satellite simulation tool software STK (Satellite Tool Kit). The results are shown in Fig. 2.

Figure 2(a) has shown that IGSO satellite and MEO satellite can have mutual visibility in 98.55% of the total simulation cycle. From Fig. 2(b) we can sum up the following rules of the variation of inter satellite link distance between IGSO and MEO: with the motion of satellites, the inter satellite link distance decreases and increases for many times within a wide range of variation in the total simulation cycle.

PRINCIPLE OF INTERSATELLITE DYNAMIC TWO-WAY TIME TRANSFER

Principle of inter satellite two-way time transfer: The principle of inter satellite two-way time transfer is shown in Fig. 3 (Huang *et al.*, 2008). Radio transmitters and receivers are mounted on satellites A and B. A and B transmit time transfer signals to each other simultaneously and receive the time transfer signals from respective counterparts, then the following equations can be obtained:

$$T_1 = \Delta t + t_2 + \tau_{BA} + r_1 + \delta_1 \quad (5)$$

$$T_2 = -\Delta t + t_1 + \tau_{AB} + r_2 + \delta_2 \quad (6)$$

In the equations, Δt is the clock offset between satellites A and B, T_1 is the time difference from satellite A's transmitting timing signals to its receiving timing signals transmitted by satellite B, t_2 is the time delay of the transmitter on satellite B, τ_{BA} is the propagation delay from satellite B to satellite A, r_1 is the time delay of the receiver on satellite A and δ_1 represents other delays; T_2 is the time from satellite B's transmitting timing signals to its receiving timing signals transmitted by satellite A, t_1 is the time delay of the transmitter on satellite A, τ_{AB} is the propagation delay from satellite A to satellite B, r_2 is the time delay of the receiver on satellite B and δ_2 represents other delays.

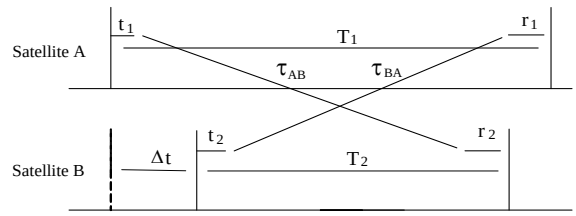


Fig. 3: Principle of inter satellite two-way time transfer

Formula (5) and (6) are processed to obtain the clock offset between the two satellites as follows:

$$\Delta t = \frac{T_1 - T_2}{2} + \frac{t_1 - t_2}{2} + \frac{r_2 - r_1}{2} + \frac{\tau_{AB} - \tau_{BA}}{2} + \frac{\delta_2 - \delta_1}{2} \quad (7)$$

In formula (7), T_1 and T_2 can be measured through satellites A and B and t_1, t_2, r_1 and r_2 can be calibrated beforehand according to the frequency of signals transmitted by satellites. When satellites A and B send to each other timing signals with similar frequencies, the links are symmetrical and their propagation delays are approximately the same, i.e., $\tau_{BA} = \tau_{AB}$; meanwhile, the clock offset Δt between the two satellites can be solved with the impact of other delays being ignored.

To analyze the impact of satellite motions on clock offset calculation, clock offset Δt between two satellites is presumed unchanged in the process of time transfer; meanwhile, the impact of time delays of the transmitter and the receiver as well as other delays are neglected and formulas (5), (6) and (7) are simplified as:

$$T_1 = \Delta t + \tau_{BA} \quad (8)$$

$$T_2 = -\Delta t + \tau_{AB} \quad (9)$$

$$\Delta t = \frac{T_1 - T_2}{2} \quad (10)$$

From (8) and (9), the calculation formula for inter satellite pseudo range is obtained as follows:

$$\rho = c\frac{T_1 + T_2}{2} \quad (11)$$

c represents the velocity of light, ρ is the inter satellite pseudo range and formulas (8), (9), (10) and

(11) are the calculation formulas for inter satellite clock offset and inter satellite pseudo range with satellite motions being taken into account and these formulas are obtained with the method of inter satellite two-way time transfer.

Principle of inter satellite dynamic two-way time transfer: According to the simulation results of link distance variation range between IGSO and MEO satellite above, as the mobile satellites is under rapidly moving condition, the path of two-way time transfer signal could be totally different, leading to diversified two-way delays. Generally the equation $\tau_{BA} = \tau_{AB}$ does not hold when the two-way time transfer algorithm is used to calculate inter satellite clock offset. Hence, the prerequisites of same signal path and delay of two-way time transfer cannot be met. The result obtained with formula (10) does not equal to the actual clock offset and correction has to be made.

A situation of two-way time transfer with IGSO and MEO satellites is considered. The impact of the motions of mobile satellite on the propagation delay of two-way time transfer signals in this situation is analyzed.

Suppose satellite B first moves towards satellite A, then moves away from satellite A. The impact of satellite motion on the propagation delay of two-way time transfer signals is discussed with two situations respectively, as follows (Huang *et al.*, 2009, 2010):

1. **When satellite B approaches satellite A:** It can be seen that τ_{BA} is greater than τ_{AB} in this situation. Therefore, the time difference T_2 of satellite B obtained with formula (9) will be smaller than that measured when satellite B is still. If formula (10) is still adopted for clock offset calculation, then the result will be greater than the actual clock offset and has to be corrected. The correction value will be $(\tau_{AB} - \tau_{BA})/2$ exactly.
2. **When satellite B keeps away from satellite A:** It can be seen that τ_{BA} is smaller than τ_{AB} in this situation. Therefore, the time difference T_2 of satellite B obtained with formula (9) will be greater than that measured when satellite B was still. If formula (10) is still adopted for clock offset calculation, then the result will be smaller than the actual clock offset and has to be corrected. The correction value will be $(\tau_{AB} - \tau_{BA})/2$ exactly.

With both the situations 1) and 2) being considered above and according to the range between satellites A and B decreasing and then growing, the inter satellite clock offset obtained with the algorithm of two-way satellite time transfer will also vary from being greater than the actual clock offset to being smaller than that accordingly. In this variation process, there will be a certain moment when the clock offset obtained with inter satellite two-way method is the closest to the actual clock offset. At the moment when the range between satellites A and B is the smallest, the propagation delays of two-way time transfer signals of the satellites will be the closest to each other. So the clock offset obtained at this moment with two-way time transfer will bear the least difference from the actual clock offset.

Based on the above analysis, two polynomials can be used to fit the sequences of pseudo range and clock offset between satellites A and B, which are obtained with the two-way time transfer method in this variation process. The minimum inter satellite pseudo range is obtained with the pseudo-range polynomial and the moment corresponding to the minimum is the one when the calculated inter satellite clock offset is the closest to the actual clock offset. With this moment being introduced into the clock offset polynomial, the inter satellite clock offset with the smallest error in the transfer process can be solved. Compared with the two-way time transfer algorithm in which satellites are supposed to be in relatively static state, this two-way time transfer algorithm with satellite motions taken into account is known as the algorithm of inter satellite dynamic two-way time transfer. In the following section, the method to solve the inter satellite clock offset with the smallest error with the inter satellite dynamic two-way time transfer algorithm will be discussed.

The sequences of inter satellite pseudo range and clock offset are obtained through calculation with the algorithm of dynamic two-way time transfer, then polynomial fitting is performed on the two sequences separately.

Suppose the fitting polynomial of fitted inter satellite pseudo-range sequence is:

$$p = f_1(t) \quad (12)$$

The fitting polynomial of inter satellite clock-offset sequence is:

$$\Delta t = f_2(t) \quad (13)$$

In formula (12) let:

$$\frac{df_1(t)}{dt} = 0 \quad (14)$$

Formula (14) is solved and moment t_3 corresponding to the minimum inter satellite pseudo range ρ_{min} can be obtained. Moment t_3 is substituted into formula (13):

$$\Delta t = f_2(t_3) \quad (15)$$

Formula (15) is solved and inter satellite clock offset with the smallest error corresponding to the minimum inter satellite pseudo range can be obtained.

ANALYSIS ON SIMULATION RESULTS

The actual clock offset between satellites A and B was assumed as 1μs and three data segments of dynamic two-way time transfer were generated through STK. With delays of equipment on the receiver and transmitter on satellites as well as other delays being ignored, the sequences of pseudo range and clock offset between satellites A and B were obtained. The results of Minimum Square fitting of pseudo range and clock offset during different transfer periods are shown in Table 1. The minimum square fitting curves of pseudo range and clock offset are shown in Fig. 4 (Huang *et al*., 2012).

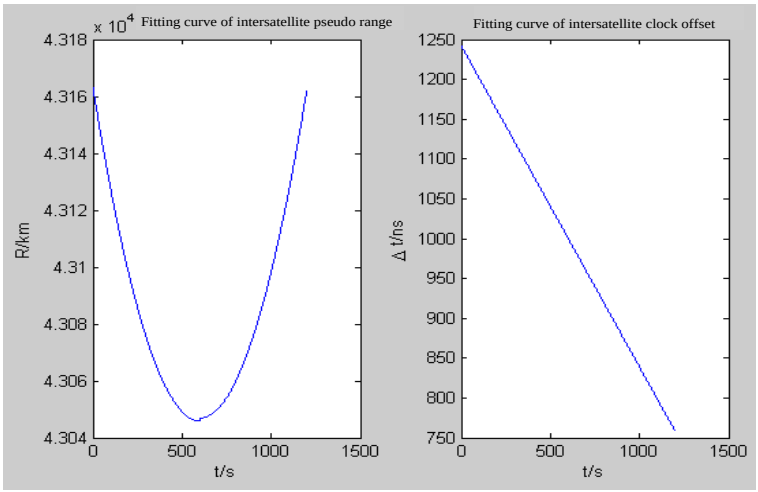
From the comparison table of fitting results from different transfer periods and the fitting curves of inter satellite pseudo range and clock offset, it can be seen that the clock offset obtained with the algorithm of inter satellite dynamic two-way time transfer based on mobile satellite is very close to actual clock offset. The simulation results of the algorithm proved the correctness of the proposed model and algorithm of inter satellite dynamic two-way time transfer.

As shown in Fig. 4(a), (b) and (c), when transfer periods begin at moments relatively symmetrical with the occurrence of minimum inter satellite range, the error of polynomial fitting is small and the accuracy of time transfer is high. The minimum error is 0.083661136117 ns.

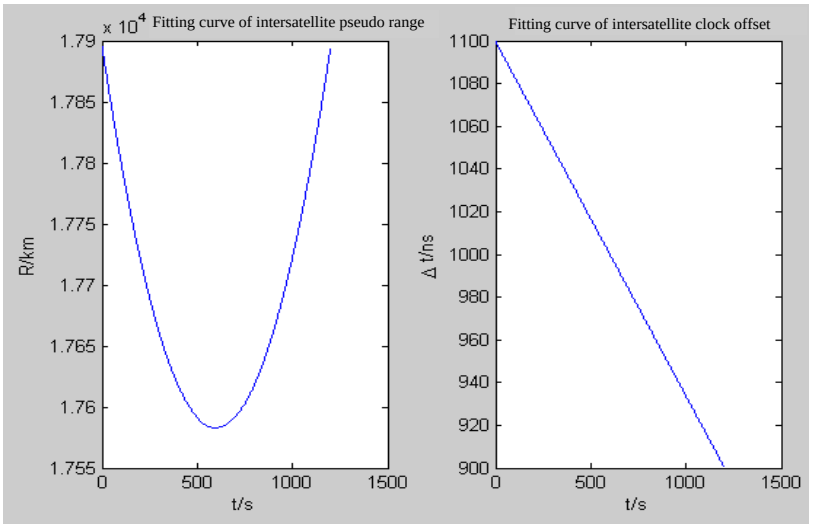
From Fig. 4 and Table 1 we can conclude that when the algorithm of inter satellite dynamic two-way time transfer is applied in the time transfer of mobile satellites, the period of two-way time transfer should begin at moments basically and relatively symmetrical with the occurrence of minimum inter satellite range so as to reduce the error of polynomial fitting and improve the accuracy of time transfer.

Table 1: Comparison of results of minimum square fitting during different time transfer periods (Jun 1-Jun 2, 2008)

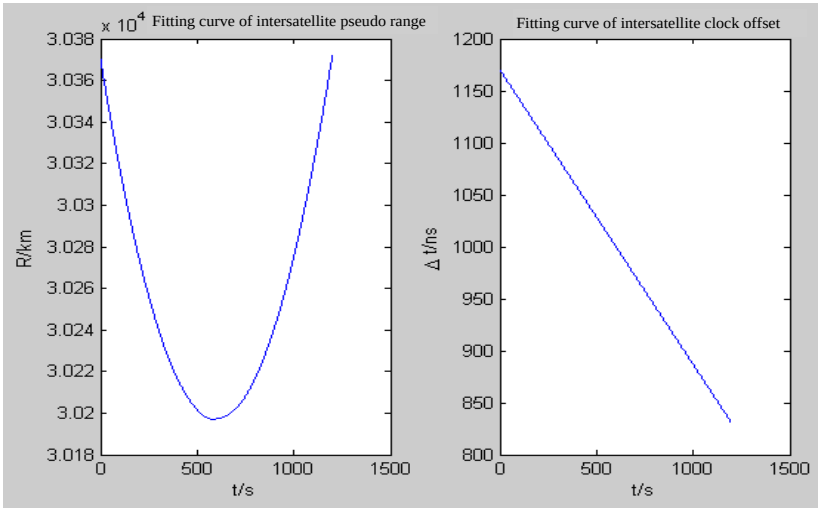
Periods	15:48:07.000-16:08:07.000 (1 Jun 2008)	00:17:14.000-00:37:14.000 (2 Jun 2008)	08:27:52.000-08:47:52.000 (2 Jun 2008)
Fitting polynomial of pseudo range	$p = 0.0003233691\ t^2 - 0.3876500168\ t + 43162.5778059630$	$p = 0.0008679949\ t^2 - 1.0412767821\ t + 17895.5309553557$	$p = 0.0004842275\ t^2 - 0.5793507181\ t + 30370.3832518086$
Moments corresponding to minimum pseudo range ρ_{min} (s)	599.3924225307587	599.8173620170098	598.2216134908996
Fitting polynomial of clock offset	$\Delta t = -0.40329850704\ t + 1242.11049033640$	$\Delta t = -0.16597778324\ t + 1099.64001723152$	$\Delta t = -0.28334855458\ t + 1170.10000242256$
Minimum clock offset Δt_{min} (ns)	1000.376421199129	1000.083661136117	1000.594772919365



(a) Fitting results of 20 min of transfer from 15:48:07.000, Jun 1, 2008 to 16:08:07.000, Jun 1, 2008



(b) Fitting results of 20 min of transfer from 00:17:14.000, Jun 2, 2008 to 00:37:14.000, Jun 2, 2008



(c) Fitting results of 20 min of transfer from 08:27:52.000, Jun 2, 2008 to 08:47:52.000, Jun. 2, 2008

Fig. 4: Fitting curves of pseudo range and clock offset between satellite IGSO and MEO

CONCLUSION

On the basis of mobile satellite mutual visible models and two-way time transfer algorithm, the impact of satellite motions on the two-way time transfer algorithm was analyzed and the algorithm of inter satellite dynamic two-way time transfer for solving high-accuracy inter satellite clock offset through combination of fitting polynomials of inter satellite pseudo range and clock offset was proposed. Simulation on actual satellite data shows that the algorithm can restrain the transfer error of inter satellite clock offset within 1 ns provided with Minimum Square fitting, the two-way time transfer periods beginning at moments basically symmetrical with the occurrence of minimum inter satellite range relatively and the impact of other factors being taken into account. The algorithm can be used for high-accuracy time transfer of mobile satellites.

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