Algorithm of Intersatellite Dynamic Two-way Time Transfer Based on GEO Satellite

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Abstract—**Two-way time transfer is a common method applied to spacecrafts and ground stations to carry out time transfer. This method improved the accuracy of time transfer by eliminating the impact of propagation paths and extra delay caused by atmosphere, so the algorithm of two-way satellite time transfer is presently one of the time transfer methods with high accuracy. 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.**

On the basis of two-way satellite time transfer algorithm, the characteristics of the propagation delay of two-way time transfer signals between MEO satellite and GEO satellite varying with intersatellite range were analyzed, and the rule of intersatellite clock offset varying with intersatellite range obtained with this algorithm was deduced. This paper presents a dynamic two-way time transfer algorithm(DTWTTA) with which high-accuracy intersatellite clock offset is solved through the combination of intersatellite pseudo-range polynomial fitting and clock-offset polynomial fitting. Simulation data of actual satellites showed that with the algorithm the intersatellite time transfer error can be controlled within 5ns provided with minimum square fitting, the two-way time transfer periods beginning at moments basically symmetrical with the occurrence of minimum intersatellite range relatively, and the impact of other factors being taken into account. As a result the algorithm can be used for intersatellite high-accuracy time transfer.

I. INTRODUCTION

Two-way time transfer is a common method applied to spacecrafts and ground stations to carry out time transfer[1,2]. 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. Reference [3] introduced a method of satellite-ground two-way time transfer for MEO satellites; An algorithm for processing data of intersatellite two-way matching measurement in formation flying satellites was deduced [4], with the motions of satellites being taken into account; Reference [5] gave the data processing results of dynamic two-way satellite time transfer conducted with commercial satellite modem. Through analysis on the rule of the propagation delay of two-way time transfer signals between MEO satellite and GEO satellite varying with intersatellite range, this paper presents an algorithm of dynamic two-way time transfer with which high-accuracy intersatellite clock offset is solved through the combination of intersatellite pseudo-range polynomial fitting and clock-offset polynomial fitting. As a result the DTWTTA is applied to high-accuracy time transfer of moving satellites.

II. PRINCIPLE OF INTERSATELLITE TWO-WAY TIME TRANSFER

The principle of intersatellite two-way time transfer is shown in Fig. 1 [6]. 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:

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

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

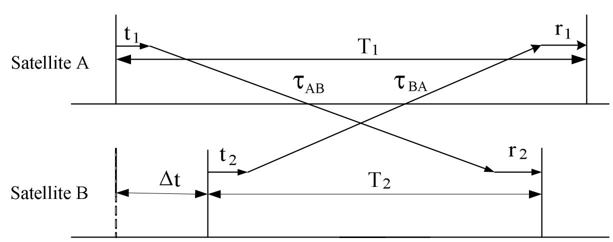

Figure 1. Principle of intersatellite two-way time transfer

In the equations, Δt is the clock offset between satellites A and B, T_1 is the time difference from satellite A's transmitting

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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.

To obtain the clock offset Δt between the two satellites, subtract (2) from (1):

$$T_1 - T_2 = 2\Delta t + (t_2 - t_1) + (r_1 - r_2) + (\tau_{BA} - \tau_{AB}) + (\delta_1 - \delta_2) \tag{3}$$

Formula (3) is processed to obtain the clock offset between the two satellites as follows:

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

In formula (4), $T_1$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. τ_{BA} equals to τ_{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 (1), (2) and (4) are simplified as:

$$T_1 = \Delta t + \tau_{BA} \tag{5}$$

$$T_2 = -\Delta t + \tau_{AB} \tag{6}$$

$$\Delta t = \frac{T_1 - T_2}{2} \tag{7}$$

From (5) and (6), the calculation formula for intersatellite pseudo range is obtained as follows:

$$\rho = c\frac{T_1 + T_2}{2} \tag{8}$$

c represents the velocity of light, ρ is the intersatellite pseudo range, and formulas (5), (6), (7) and (8) are the calculation formulas for intersatellite clock offset and intersatellite pseudo range with satellite motions being taken into account, and these formulas are obtained with the method of intersatellite two-way time transfer.

III. Analysis on Propagation Delay of Two-Way Time Transfer Signals Between MEO Satellite and GEO Satellite

Since satellites like MEO moves at high speeds, generally the equation $\tau_{BA} = \tau_{AB}$ does not hold when the two-way time transfer algorithm is used to calculate clock offset. Therefore, the clock offset obtained with formula (7) does not equal to the actual clock offset, and correction has to be made.

A situation of two-way time transfer with GEO and MEO satellites is considered. The transfer scheme is shown in Fig. 2. The impact of the motions of MEO satellite on the propagation delay of two-way time transfer signals in this situation is analyzed.

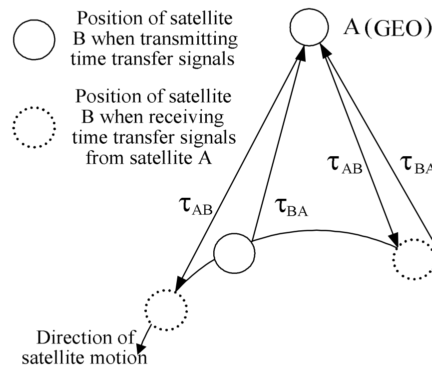


Figure 2. Scheme of delay variation in propagation of satellite two-way time transfer signals following intersatellite range

The direction of satellite motion is shown in the figure: 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:

A. When satellite B approaches satellite A

It can be seen from Fig. 2 that τ_{BA} is greater than τ_{AB} in this situation. Therefore, the time difference T_2 of satellite B obtained with formula (6) will be smaller than that measured when satellite B is still. If formula (7) 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.

B. When satellite B keeps away from satellite A

It can be seen from Fig. 2 that τ_{BA} is smaller than τ_{AB} in this situation. Therefore, the time difference T_2 of satellite B obtained with formula (6) will be greater than that measured when satellite B was still. If formula (7) 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.

IV. Algorithm of Intersatellite Dynamic Two-Way Time Transfer

A.. Principle of dynamic two-way time transfer

With both the situations III.A and III.B being considered above, and according to the range between satellites A and B decreasing and then growing, the intersatellite 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 intersatellite 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 intersatellite pseudo range is obtained with the pseudo-range polynomial, and the moment corresponding to the minimum is the one when the calculated intersatellite clock offset is the closest to the actual clock offset. With this moment being introduced into the clock offset polynomial, the intersatellite 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 dynamic two-way time transfer. In the following section, the method to solve the intersatellite clock offset with the smallest error with the dynamic two-way time transfer algorithm will be discussed.

B. Method of calculating intersatellite clock offset with dynamic two-way time transfer algorithm

The sequences of intersatellite 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 intersatellite pseudo-range sequence is:

$$\rho = f_1(t) \tag{9}$$

The fitting polynomial of intersatellite clock-offset sequence is:

$$\Delta t = f_2(t) \tag{10}$$

In formula (9):

$$\text{Let} \quad \frac{df_1(t)}{dt} = 0 \tag{11}$$

Formula (11) is solved, and moment t_3 corresponding to the minimum intersatellite pseudo range ρ_{min} can be obtained. Moment t_3 is substituted into formula (10):

$$\Delta t = f_2(t_3) \tag{12}$$

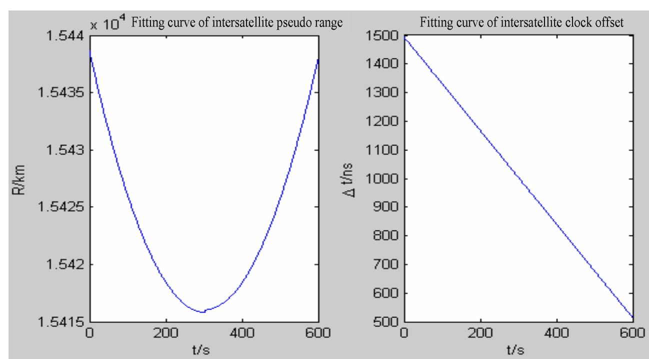
Formula (12) is solved, and intersatellite clock offset Δt_{min} with the smallest error corresponding to the minimum intersatellite pseudo range can be obtained.

V. ANALYSIS ON SIMULATION RESULTS

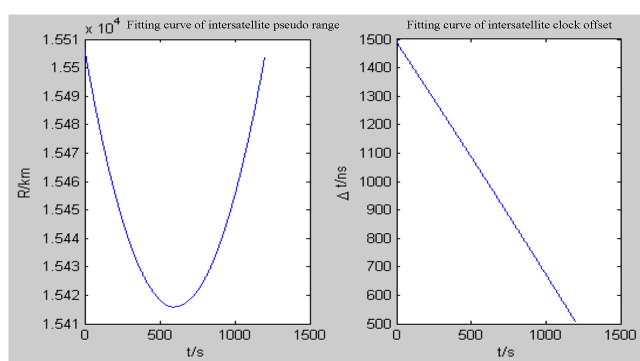
To test the above algorithm, BeiDou-1C ($E110.50^{\circ}$) was adopted as GEO satellite (satellite A), and SHI_JIAN-6A (the height of orbit was altered to 21000km) as MEO satellite (satellite B). The actual clock offset between satellites A and B was assumed as $1\mu s$, and four data segments of dynamic 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 I. The minimum square fitting curves of pseudo range and clock offset are shown in Fig. 3.The minimum square fitting curves of pseudo range and clock offset are shown in Fig. 3.

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

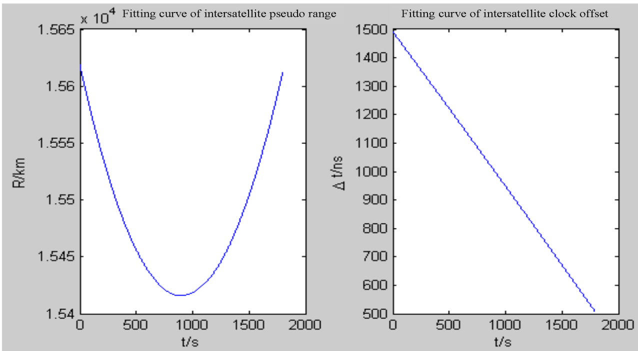
As shown in Fig. 3(a), (b) and (c), when transfer periods begin at moments relatively symmetrical with the occurrence of minimum intersatellite range, the error of polynomial fitting is small, and the accuracy of time transfer is high. The minimum error is 0.254122631050ns.



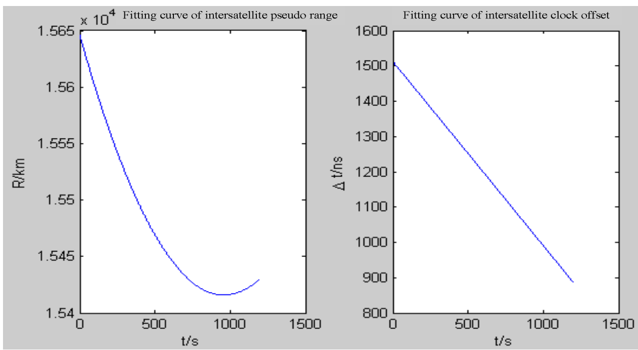
(a) Fitting results of 10 minutes of transfer from 00:46:00.000, Jun 2nd, 2004 to 00:56:00.000, Jun 2nd, 2004



(b) Fitting results of 20 minutes of transfer from 00:41:00.000, Jun 2nd, 2004 to 01:01:00.000, Jun 2nd, 2004



(c) Fitting results of 30 minutes of transfer from 00:36:00.000, Jun 2nd, 2004 to 01:06:00.000, Jun 2nd, 2004



(d) Fitting results of 20 minutes of transfer from 00:35:00.000, Jun 2nd, 2004 to 00:55:00.000, Jun 2nd, 2004

Figure 3. Fitting curves of pseudo range and clock offset between satellite A and B

As shown in Fig. 3(d), when two-way transfer periods begin at moments relatively unsymmetrical with the occurrence of minimum intersatellite range, the error of polynomial fitting is large, and the accuracy of time transfer decreases. The error reaches -3.8780787248468ns.

Therefore, when the algorithm of dynamic two-way time transfer is applied in the time transfer of moving satellites, the period of two-way time transfer should begin at moments basically and relatively symmetrical with the occurrence of minimum intersatellite range so as to reduce the error of polynomial fitting and improve the accuracy of time transfer.

VI. CONCLUSIONS

On the basis of two-way time transfer algorithm, the impact of satellite motions on the algorithm was analyzed, and the algorithm of dynamic two-way time transfer for solving high-accuracy intersatellite clock offset through combination of fitting polynomials of intersatellite pseudo range and clock offset was proposed. Simulation on actual satellite data showed that the algorithm can restrain the transfer error of intersatellite clock offset within 5ns provided with minimum square fitting, the two-way time transfer periods beginning at moments basically symmetrical with the occurrence of minimum intersatellite range relatively, and the impact of other factors being taken into account. The DTWTTA can be used for high-accuracy time transfer of moving satellites.

TABLE I. COMPARISON OF RESULTS OF MINIMUM SQUARE FITTING DURING DIFFERENT SYNCHRONIZATION PERIODS(JUN 2ND, 2004)

Periods	00:46-00:56(10min)	00:41-01:01(20min)	00:36-01:06(30min)	00:35-00:55 (20min, unsymmetry)
Fitting polynomial of pseudo range	ρ=0.0002483650 t^2 -0.1499342706 t + 15438.5602934204	ρ=0.0002477680 t^2 -0.2988975634 t +15506.1012307209	ρ=0.0002468473 t^2 -0.4466696970 t +15618.1232744282	ρ=0.0002490508 t^2 -0.4792484650 t + 15646.4862102770
Moments corresponding to minimum pseudo range ρ_{min}(s)	301.8426471161639	603.1803391186274	904.7489051253945	962.1499808095442
Fitting polynomial of clock offset	Δt=-0.00015816345t^2 -1.53954688672t +1484.67117598528	Δt=-0.00001976153t^2 -0.79604618535t +1489.03134978649	Δt=-0.00000580814t^2 -0.53817735552t +1491.92387211386	Δt=-0.00130047355t^2 +1.03866183620t +1200.66419441944
Minimum Clock offset Δt_{min} (ns)	1005.560157058491	1001.682174653436	1000.254122631050	996.1219212751532

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