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A Fast Detection Method of Pseudo-Range Jump

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Abstract. In view of the large workload and low efficiency in precisely determining pseudo-range jump time in the two-way ranging time synchronization of the navigation system, a method for rapid determination of pseudo-range jump based on clock drift rate estimation and binary search was proposed. The method took advantage of the property that the drift rate of on-board atomic clock is relatively stable over a long period of time. Firstly, the correct clock drift rate was calculated from the uplink and downlink pseudo-ranges according to the pseudo-range observing equations. Afterwards, the potential time period during which jump occurred was divided equally, producing two sub time periods. Two clock drift rate values and two jump quantities were solved respectively from the pseudo-range data of the above two sub time periods, and the next potential time period was the one with the larger jump quantity. The above procedure was repeated until the final potential time period was short enough. Finally, the precise jump time was determined by difference with the data in the final potential time period. Experimental results illustrate the correctness and effectiveness of the proposed method.

Keywords. Time synchronization; Pseudo-range jump; clock drift rate; binary search

1. Introduction

In the ground control segment of Beidou satellite navigation system, the radio two-way ranging is generally applied for satellite-ground, inter-station and inter-satellite time synchronization[1] [2]. However, due to the accumulation of frequency error in the time-frequency system, transmitting and receiving equipment failure, equipment instability and a variety of unpredictable random factors, step jump often occurs during uplink and downlink ranging, thereby affecting the calculation and prediction result of the satellite-ground, inter-station or Inter-satellite clock difference, and introducing large error in clock difference. In order to investigate the problem and recover the time synchronization result as soon as possible, the jump time should be determined.

The traditional method for locating jump is to traverse through all the uplink and downlink pseudo-range observations to find it. Generally, the first difference and the second difference are obtained by dividing into small sections, and then the difference results are fitted to the curve to find the jump point. Since there is one observation value

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per second, the amount of observation data is huge. There-fore, such traversal search is very blind and inefficient, which is time-consuming and labor-intensive, and greatly prolongs the time of system failure, affects the timeliness of problem discovery and resolution, and restricts the rapid recovery of the system, which in turn leads to long-term unavailability of the system.

In order to find problems and troubleshoot in time, it is necessary to quickly discover the jump, determine the size of the jump, determine the link (uplink or downlink) that caused the jump, and locate the moment when the jump occurred.

Huang et al. [3] proposed a time synchronization outlaw elimination method and filtering method between stations to solve the problem of time difference measurement value caused by uncertain factors, which improve the performance of time synchronization between stations. In view of the satellite time frequency system abnormality caused by power off and restart of the load time system, Chen et al. [4] proposed a strategy for inter-satellite link error correction using ranging and data transmission functions of inter-satellite link. Liu et al. [5] proposed a cooperative time synchronization method via laser/radio inter-satellite links. The simulation results showed that the stability in the short and medium terms of the time reference generated with the proposed method is significantly improved compared with that generated via radio inter-satellite links. LV et al. [6] proposed a method of the two-way satellite-ground time synchronization under inter-satellite links system. experimental results showed the 10000s frequency stability of the Satellite clock difference is better than 8×10^{-14}.

In this paper, an approach for rapid detection of pseudo-range jump and precise calculation of jump quantity and jump time, which is based on clock drift rate estimation and binary search, is presented.

2. Methods

2.1. Principle of the Approach

Set L_{u}^{t}, L_{d}^{t} are the uplink and downlink pseudo-range at t(s) (One observed pseudo-range value is produced every second), according to the pseudo-range observation equation [7], we can obtain the following two equations:

$$L_{\mathrm{u}}^{t} = D^{t} + T_{\mathrm{s}}^{t} - T_{\mathrm{g}}^{t} + N + M_{\mathrm{r}} + C_{\mathrm{u}} \tag{1}$$

$$L_{\mathrm{d}}^{t} = D^{t} + T_{\mathrm{g}}^{t} - T_{\mathrm{s}}^{t} + N + M_{\mathrm{s}} + C_{\mathrm{d}} \tag{2}$$

where D^{t} is the true distance of satellite and Antenna phase center at time t; T_{s}^{t} and T_{g}^{t} are satellite clock error and ground clock error and T_{g}^{t} is 0 at master station. We can obtain: $T^{t} = T_{\mathrm{s}}^{t} - T_{\mathrm{g}}^{t}$, where T^{t} is the satellite-ground clock difference.

N contains the ionospheric delay and tropospheric delay at the observed time; M_{r}, M_{s} are respectively the receiver and transmitter link device delay of the satellite; C_{u},

C_d (constant value, calibrated initially from the know values) are the zero value or the equipment delay of the uplink and downlink (including the uplink and downlink digital unit and analog unit, the up and down converter, the power amplifier or the low noise amplifier, etc.), respectively.

The following equation can be obtained by subtracting Eq. (1) and Eq. (2).

$$dL = L_u^t - L_d^t = M + C + 2T^t \tag{3}$$

where: $C = C_u - C_d$, $M = M_r - M_s$; T^t is the satellite-ground clock difference at time *t*.

If t_0 and t_1 are known, according to Eq. (3) we can obtain the following two equations:

$$dL_0 = L_u^{t_0} - L_d^{t_0} = C + M + 2T^{t_0} \tag{4}$$

$$dL_1 = L_u^{t_1} - L_d^{t_1} = C + M + 2T^{t_1} \tag{5}$$

where T^{t_0}, T^{t_1} are respectively the satellite-ground clock difference at time t_0 and t_1.

According to the operation characteristics of the atomic clock, the relationship between T^{t_0} and T^{t_1} can be approximately expressed as [8][9]:

$$T^{t_1} = T^{t_0} + a_1\Delta t + a_2\Delta t^2/2 + \varepsilon(\Delta t) \tag{6}$$

or:

$$T^{t_1} - T^{t_0} = a_1\Delta t + a_2\Delta t^2/2 + \varepsilon(\Delta t)$$

where: $\Delta t = t_1 - t_0$; a_1 and a_2 are respectively the satellite clock drift rate (rate of clock drift) and the rate of the satellite clock drift rate (clock drift acceleration); $\varepsilon(\Delta t)$ is the random variation of satellite clock time deviation, which is set to 0 for simplification.

So the clock drift quantity from time t_0 to t_1 can be expressed as:

$$T_f = a_1\Delta t + a_2\Delta t^2/2$$

Since the on-board atomic clock has the characteristic of high frequency stability (better than 10^{-14}/day [10]), the clock drift rate a_1 is generally stable in a period of time. Based on this, we can determine the occurrence of pseudo-range jump by solving the clock drift rate a_1.

2.2. Clock Drift Solving

We can obtain the following equation by subtracting Eqs. (5) and (4):

$$dL_1 - dL_0 = 2a_1\Delta t + a_2\Delta t^2 = 2T_\mathrm{f} \tag{7}$$

where: $a_1\Delta t$ is the variation of clock bias caused by clock drift, $a_2\Delta t^2/2$ is the variation of clock bias caused by the rate of clock drift.

During the time range of several days, i.e., Δt is within the Middleweight of 10^5 seconds, we can approximately get that: $2a_1\Delta t >> a_2\Delta t^2$, so we can set $a_2\Delta t^2 \approx 0$ in Eq. (7), and then it can be obtained that:

$$a_1 = {}^{2T_\mathrm{f}}\!/_{2\Delta t} = {}^{(dL_1 - dL_0)}\!/_{2\Delta t} \tag{8}$$

By combining Eqs. (4), (5), (7), (8), we can express a_1 as:

$$a_1 = ((L_\mathrm{u}^{t_1} - L_\mathrm{d}^{t_1}) - (L_\mathrm{u}^{t_0} - L_\mathrm{d}^{t_0}))/(2(t_1 - t_0))$$
(9)

In Eq. (9), the impact of uplink and downlink delay is completely eliminated, and the clock drift rate only related to the uplink and downlink pseudo-range values. Given that the measurement accuracy is high enough, it can be guaranteed that the calculated value of the clock drift rate achieves the appropriate accuracy.

The traditional method obtains the clock drift by fitting a quadratic curve from a series of clock error values [11],which needs large amount of data and cost large amount of calculation.

2.3. Jump Detection

If obvious pseudo-range jump occurred in the period of time from t_0 to t_1 in the uplink or downlink ranging, assuming the uplink pseudo-range jumped J_u, Eq. (5) is transformed into:

$$dL_1' = dL_1 + J_\mathrm{u} = L_\mathrm{u}^{t_1} + J_\mathrm{u} - L_\mathrm{d}^{t_1} = C + 2T^{t_1}$$

and Eq. (7) and Eq. (8) respectively transformed to:

$$dL_1 + J_\mathrm{u} - dL_0 = 2T_\mathrm{f} \tag{10}$$

$$a_1' = {}^{(dL_1 - dL_0 + J_\mathrm{u})}\!/_{2\Delta t} \tag{11}$$

Comparing the expressions of a_1 as Eq. (8) and a_1' as Eq. (11), we can see that if there is a jump, an error E_{a_1}, which is the error between the calculated value and the true value, would be introduced into the solution of the clock drift rate a_1',

$$E_{a_1} = a_1' - a_1 = {}^{J_u}\!/_{2\Delta t} \tag{12}$$

From Eq. (12), we can see that the error between the calculated rate and the true value of the rate increases as the time range shortens.

Provided that the error of the clock drift rate is known, the pseudo-range hopping quantity could be expressed as:

$$J_u = E_{a_1} \times 2\Delta t \tag{13}$$

It can be seen from Eq. (12), that the error of the clock drift rate E_{a_1} changes with the length of the time interval Δt during which the jump occurred. So we can not determine if there is jump or not during the time interval Δt according to the quantity of E_{a_1}. Fortunately, while the hopping quantity J_u is a fixed value, we can calculate J_u according to Eq. (13) further, and use the absolute value of J_u as the criterion of whether jump occurred or not.

2.4. Process Flow

According to the above theory, the following four steps are conducted to determine the pseudo-range jump time.

(1) Calculating the true value of clock drift rate. According to Eq. (9), we can get the value of clock drift rate by using the true uplink and downlink pseudo-range measurements in a certain period which is near the potential jump period, and the true value comes from the mean value of multiple results computed by using multiple groups of data (not less than 5 groups).

(2) Determining the initial jump period and calculate the jump. First, the pseudo-range measurements near the start and end time of the time period to be examined are used for solving the clock drift rate of this period according to Eq. (9), and the jump quantity $\|J_u\|$ is solved according to Eq. (13) subsequently. If $\|J_u\|$ is within the tolerable range (<10ns), it is assumed that there is no jump in this period and we have to continue to examine the data of other time period. Otherwise, there should be a pseudo-range jump in this period, and the period is marked as potential jump period, on which a series of operations will be conducted subsequently.

It should be noted that the 10ns threshold here for determining whether the jump occurs or not based on two reasons: First, pseudo-range measurements occasionally have less than 10ns random fluctuations; the second is the frequency rate of the satellite atom clock generally lies in the order of 10^{-14}/day [12]. So that if the interval between the data used for solving the instant clock drift rate and the data used for the true clock drift rate is within the range of 10^5 seconds (within 10 days), it could be guaranteed that the clock drift rate would be less than 10^{-3}ns/s, and then the obtained jump quantity $\|J_{\mathrm{u}}\|$ according to Eq. (13) within 10ns.

(3) Fine positioning of the jump period. First, the potential time period is divided into two periods equally; Then the clock drift rate and the jump quantity of the two periods are solved respectively so as to determine in which jump occurred, and the one with the larger jump quantity is the target; Finally, the potential jump period is updated with the target period.

The above process is repeated to subdivide the potential jump period until the potential period is short enough.

Repeat the above process to continuously subdivide the potential jump period until the potential period is shortened to less than one hour (for a period shorter than one hour, the amount of observed data is less than 3600, such a data scale can be directly performed difference).

(4) Jump time positioning. The potential period short enough is determined by step 3, and the uplink and downlink pseudo-range values in the period is differentiated respectively according to the following formula [13][14]:

$$\Delta L_{\mathrm{u(d)}} = L_{\mathrm{u(d)}}^{t} - L_{\mathrm{u(d)}}^{t-1}$$

And then the curve is fitted from the data obtained by difference. The jump time is accurately located according to the trip point of the curve. At the same time, it is determined that whether the jump is caused by the uplink or downlink.

It should be noted that the result of the first-order difference is the change rate of the pseudo-range, that is, the velocity of the satellite relative to the ground antenna. As to the satellite-ground time synchronization for MEO(Medium Circular Orbit) satellites and IGSO (Inclined Geosynchronous Orbit) satellites, since the acceleration of the satellite relative to the ground is large, that is, the change rate of the first-order different result is comparably large. If the pseudo-range rate variation in one second (that is the acceleration of the satellite) is larger than the jump quantity of the pseudo-range, it will lead that it’s impossible to quickly find the jump point directly from the curve fitted according to the first-order difference data. At this time, it’s needed to conduct the difference with the first-order different data, and get the second-order different data, which is used for fitting curve to determine the jump point. As to satellite-ground and inter-station time synchronization for GEO (Geostationary Orbit) satellites, the acceleration of the satellites relative to the ground is small, and the jump time can generally be determined by first-order difference.

Figure 1 shows the processing flow to determine the pseudo-range jump time.

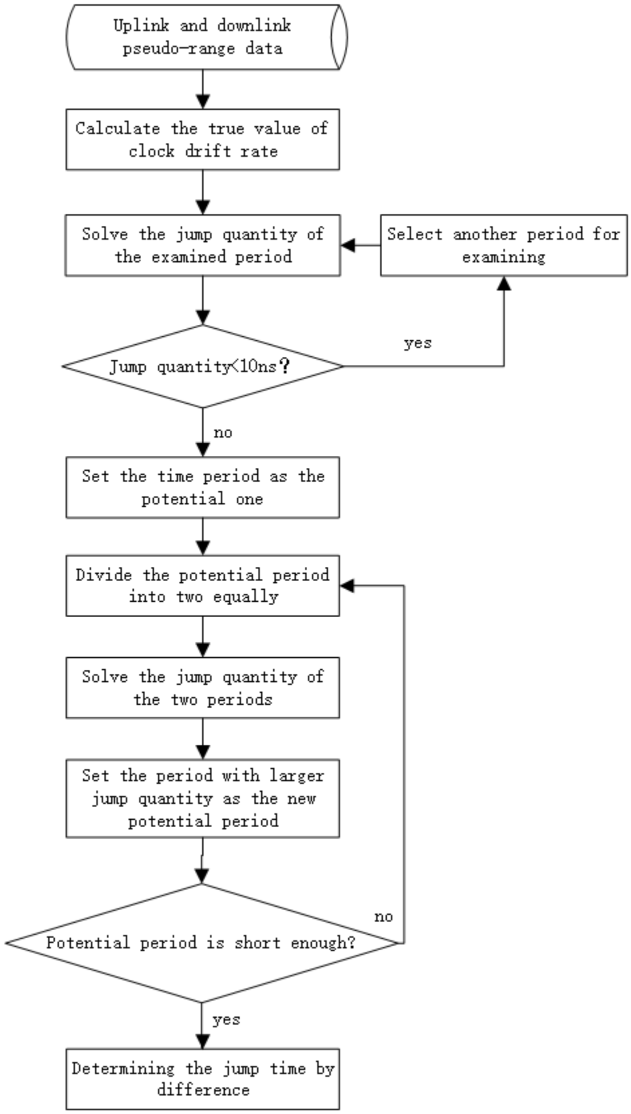

Figure 1. Flow chart of determining the pseudo-range Jump time.

2.5. Efficiency Analysis

For a *M*-seconds period to be searched, set that the binary search time is *k*, and the length of the final short period determined by binary search is *N* seconds. According to the above process, the following relationship can be obtained:

$$M = N \cdot 2^k \text{ or } k = \log_2 \tfrac{M}{N}.$$

If *M* is 10^5 of magnitude (about 10 days), and *N* is 10^3 of magnitude (about 1 hour), then $k \approx \log_2 100$, about 7 times.

It can be seen that the search period can be shortened from 10 days to 1 hour by 7 rounds of binary search, consequently the difference can be conducted with the data in the final 1 hour.

Through the process introduced in 3.1, it is possible to check whether there is pseudo-range jump afterwards. At the same time, it is possible to quickly calculate the jump quantity and position the jump moment, avoiding traverse searching the possible trip point in a large amount of observation data, and the efficiency of determining the hopping time is dramatically improved.

It should be noted that, the difference, which was conducted with the observing data of the entire potential period directly, is infeasible. The reasons are first the data volume is too large; second, the antenna does not track a satellite all through the potential time, i.e., the data set may not be continuous but be composed by some data segments. In addition, there may be some loses in the observing data occasionally, and burr jump occurred to the data randomly, resulting in not all the observing data applicable. Consequently, the jump time can not be determined directly through the first-order and second-order difference.

3. Results

In order to verify the feasibility and effectiveness of the presented method, the observing data of the Beidou satellite navigation ground test system are applied for experiment and analysis. At BDT (Beidou Time) 14:00 on April 14th, the attendant of the master station of the ground segment of BDS report a jump of the clock difference of the satellite-ground time synchronization of one satellite after BDT April 8th (not included), but did not give a specific jump time. Aim at this fault, the solution is as follows:

First of all, the uplink and downlink satellite-ground ranging data from April 8th to April 14th are extracted.

After ascertaining that the clock difference did not jump on April 8th, the data, close to the start and end time of the arc section observed from BDT 1:30 on April 8th to BDT 4:42 on April 8th, is used for solving several clock drift rate values according to Eq. (9), and all values are averaged to obtain a more accurate clock drift rate value of -0.04258ns/s, which is treated as the clock drift rate true value.

The clock drift rate value of -0.04257ns/s is obtained from the data surveyed from BDT 8:50 on April 14th to BDT 12:15 on April 14th according to Eq. (9). The error between the solved value and the true value is 0.00001ns/s. The jump quantity, which is calculated according to Eq. (11), is 0.3ns <10ns, indicating no jump occurred on April 14th.

The clock drift rate value solved from the data observed from BDT 3:20 to BDT 6:05 on April 9th and the data observed from BDT 8:25 to BDT 10:40 on April 13th is -0.04183ns/s. the error between -0.04183ns/s and the true value is 0.00075ns/s, and the jump quantity is 534.6ns> 10ns, indicating pseudo-range jump occurred during the time interval from BDT 3:20 on April 9th to BDT 10:40 on April 13th, and this period is marked as the potential jump period.

Two clock drift rate values, which are respectively -0.04198ns/s and -0.042564ns/s, are calculated from the data observed from 9th to 11th and the data from 11th to 13th. The jump quantity are respectively 531.2ns and 6.5ns, indicating jump occurred during 9th to 11th, and this period is updated as the new potential jump period.

The new potential jump period is divided again and the above procedure is repeated to find a new potential jump period. After several times of binary search, the potential jump period is narrowed to the range from BDT 3:01 to 3:55 on April 11th.

The time periods of every calculation involved and the solved parameters are shown in Table 1 (The data used for solving is near the start and end time of every period of time).

As can be seen from the data in the table, the jump time is positioned in the short time period of 3280 seconds only through four rounds of search and 11 times of calculation from the large quantity observing data of 7-day scale.

Table 1. Results of every round calculation.

Start time	End time	Δt (s)	Clock drift rate (ns/s)	Clock drift rate error(ns/s)	Jump quantity(ns)
8th 1:30	8th 4:42	10200	-0.04258	0	0
14th 8:50	14th 12:15	10800	-0.042566	0.000014	0.3
9th 3:20	13th 10:40	356400	-0.04183	0.00075	534.6
9th 3:20	11th 4:50	165600	-0.04198	0.00160	531.2
11th 1:10	13th 10:40	201600	-0.042564	0.000016	6.5
9th 3:20	10th 5:35	85800	-0.042563	0.000017	3.0
10th 2:5	11th 4:50	93600	-0.03975	0.00283	530.0
11th 1:10	11th 4:50	12600	0.02156	0.02102	529.8
11th 1:10	11th 3:0	6580	-0.042421	0.000159	2.1
11th 3:1	11th 4:50	6580	-0.00234	0.04024	529.6
11th 3:1	11th 3:55	3280	0.03814	0.08072	529.5

Finally, the first-order difference is conducted individually with the uplink and downlink pseudo-range data observed from 3: 1 to 3: 55 on April 11th. The data produced from the difference is linked as shown in figure 2 and figure 3. As can be seen from figure 3, the first-order differential curve of the downlink pseudo-range is smooth; while in figure 2, the uplink differential curve has a convex jump. By checking the transition point in figure 2, it is found that the differential pseudo-range value of the 2012th row jumped. By further examining the actual pseudo-range data in the vicinity of this row, it is found that a step jump occurred in the uplink pseudo-range from the 2013th row; that is, at BDT 3:33:32 on April 11th, a step jump occurred in the uplink pseudo-range. The jump quantity is 523ns, which is very close to the solved value of 529.5ns, verifying the correctness and effectiveness of this method.

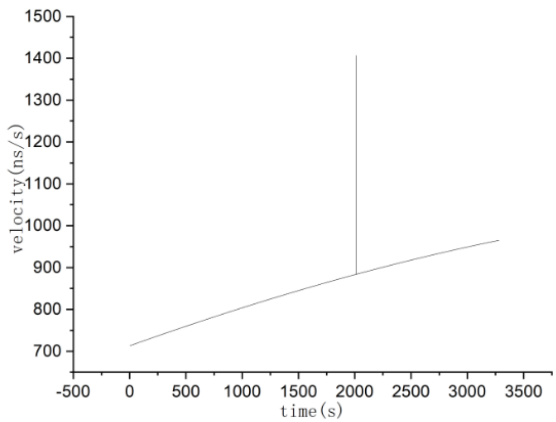

Figure 2. First-order difference of uplink pseudo-range.

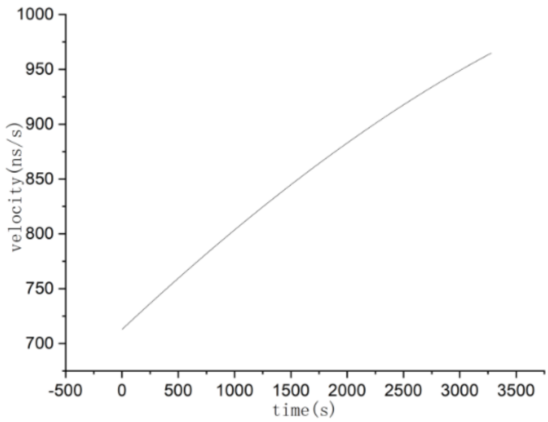

Figure 3. First-order difference of downlink pseudo-range.

After knowing the jump time and the link that triggers the jump, the corresponding device can be checked and repaired in a targeted manner, and the device delay value can be adjusted according to the jump quantity if necessary.

4. Conclusion

In this paper, we proposed a fast method to determine the pseudo-range jump based on the clock drift rate estimation and binary search by deriving a clock drift expression that contains only the observed values without uncertainties, using the property that the drift rate of atomic clocks is relatively stable over a long period of time. By applying this method, there is no need for knowing the link delays such as ionospheric delay, tropospheric delay, on-board component group delay and antenna device delay. Only based on pseudo-range observing data, we can quickly detect the jump, calculate the jump quantity and determine jump time. In addition, the searching range is exponentially reduced, avoiding traversal searching from the whole large amount observations. As a result, the efficiency is dramatically improved.

It should be noted that, in order to locate the jump time, the uplink and downlink pseudo-range observations are needed when the jump occurred. nevertheless, if the antenna is in the stow state at the jump time, that is, the uplink and downlink pseudo-range observations can not be obtained, we can still detect the jump, calculate the jump quantity and determine the time interval during which the jump occurred from the pseudo-range values in the neighboring observation periods before and after the jump time, but not the exact jump time and the link where the jump occurred. In addition, this method is only feasible for the step jump. As to the occasional glitch, that is the phenomenon jumping back after a short period when the jump occurred, this method loses effectiveness.

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