

Clock-offset computation method of space network aided by satellite clock prediction

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Abstract. A novel network clock-offset resolution method for space network is proposed in the paper. In the process of clock-offset resolution based on the network inter-node measurement data, the prediction of satellite clock result is used as the priori information. A double weighted control is made with the consideration of the point clock performance and the measurement performance, and better measurement error suppression effect is achieved. The results of simulation experiment indicated that network clock-offset resolution result with better stability and accuracy is achieved compared with the traditional Least Squares method in different scenarios.

1 Introduction

Inter satellite link is an important means to proceed the communications and measure missions, and has been widely used in space information systems, because of its long-range, wide-visible, and large transmission capacity. In BDS and GPS systems, take satellites and ground stations as nodes, and using the satellite-ground and inter-satellite links as the communications and measurement ways, a satellite-ground cooperative network is constructed. The communications time synchronization and autonomous navigation network is undertaken by the net-work. The net assures the high-quality PNT service of GNSS systems.

The time synchronization of space net is the foundation of the space-time unification and effective cooperation of network nodes. The whole net time synchronization includes two key taches: clock offset measurement and clock offset estimation. When time synchronization precision requirement is high, two way time and frequency transfer method is used to fulfil the measurement of clock offset. When the precision requirement is low, the measure method can be common view or GNSS time synchronization. Based on the maximum measure principle, every nodes should have at least one range and relative clock offset measure, during the satellite operation period. As a result, the measure data will be redundant and relative. The purpose of the whole net clock offset estimation based on the measurement data, is to fulfil the reliability verification. The abnormal data can be discovered, and the obtained clock offset will be more accurate and stable.

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Traditional whole net clock offset estimation method include least square method and Kalman method. Kalman method is used in GPS system to accomplish the clock offset and orbit combined estimation. A method based on Kalman used for GNSS system is also proposed in China by Zhujun, and the autonomous time synchronization problem is also discussed based on the modern adjustment theory. Aimed at the limitation of traditional method, a brand new whole network clock offset combined estimation method aided by clock offset prediction is proposed in the paper. The method take clock offset prediction data as the priori information, and the double restrain of clock error and measure error is fulfilled. Compared with LS method, better accuracy and stability can be realized with the method. It also has lower computation and easy using superiority relative to Kalman method.

2 Whole network clock offset combined estimation method

After the clock offset measurement between the nodes in the network, whole network clock offset estimation can be made using the measure data, and more accuracy and stable clock offset can be obtained. Traditional method includes LS method and Kalman method.

The process of LS method is shown as followings:

The measurement formula is

$$V = L - AX \quad (1)$$

In the formula(1), L is an m dimension measurement vector,

A is a $m \times n$ coefficient matrix, X is n dimension parameter vector need to be solved.

The solution of the measurement formula is based on the LS criterion, it can be written as

$$V^T P V = \min \quad (2)$$

V is the m dimension residual vector, the LS solution is

$$X = (A^T P A)^{-1} A^T P L \quad (3)$$

P is the symmetry weight matrix, and $A^T P A$ is the normal matrix.

σ_0 is the $m \times m$ parameter estimation error

$$\sigma_0 = \sqrt{V^T P V / (m - n)}, m > n \quad (4)$$

If the clock offset can be measured continuously, the sequential adjustment method can be used.

With the method, assuming that there are two measurement formula:

$$V_1 = L_1 - A_1 X, V_2 = L_2 - A_2 X \quad (5)$$

The measurement formulas are independent, and the needed vector X is the same.

Measurement weight matrixes are P_1 and P_2 . The solution method is using the

Added method.

$$(A_1^T P_1 A_1 + A_2^T P_2 A_2) X = (A_1^T P_1 L_1 + A_2^T P_2 L_2) \quad (6)$$

The estimation result is

$$X = (A_1^T P_1 A_1 + A_2^T P_2 A_2)^{-1} (A_1^T P_1 L_1 + A_2^T P_2 L_2) \quad (7)$$

LS method has the advantage of low complexity, and the whole net clock offset estimation can be made. But it lacks the using of the priori measurement information, and the continuous measure superiority cannot be utilized sufficiently.

Kalman method is to fulfill the combined clock offset estimation with the establishment of status model and measure model based on the measurement data. The stability of Kalman method is better than LS method, but it is weak in gross error restraint. Considering

about the complexity of space environment and high-dynamic of inter satellite link, the abnormal measurement and atomic clock are possible to appear, the estimation of clock offset will be influenced. Kalman method also can be combined with the orbit estimation, but the complexity will be really high. When the nodes number of the space network is big, the computation pressure will be huge. More stable and low complexity method is needed for space information network composed of variable nodes

3 Space clock prediction aided clock-offset combined estimation method of space network

If the space clock has enough stability and can be simulated and predicted accurately, the time synchronization is no longer necessary or the time synchronization frequency can be lowered extremely. Clock offset modeling relies on clock offset observations that are generally based on long term offset observations and atomic clock models with strong stability and confidence

With the aid of clock modeling and extrapolation techniques, the estimation of clock error results can be realized, and the result of time alignment can be checked and corrected according to the prior information. Therefore, a better clock error calculation result should be obtained. Based on the above analysis, the whole network time synchronization algorithm based on satellite clock forecasting is proposed.

The algorithm includes two steps: clock error modeling and forecasting and clock error estimation.

- Clock offset modeling and prediction

The process of accurately simulating and forecasting the time varying features of atomic nodes in a space node includes four steps: clock error observation, clock error model fitting, clock parameter estimation, and satellite clock modeling.

Observing the satellites by the ground station can obtain the pseudo range observations of the satellites. On this basis, the known parameters such as precision orbit parameters, station coordinates, ambiguity parameters and tropospheric delay parameters can be solved to obtain satellites Clock difference observation sequence.

Based on the acquired clock observations, in order to achieve the optimal estimation of the clock parameters, we first need to construct a precise clock error model. Taking the quadratic polynomial model including phase, frequency and frequency drift as an example, the mathematical expression of the clock error model is

$$\Delta t_i = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + v_i \quad (8)$$

In the formula, a_0, a_1, a_2 are the satellite clock parameters, corresponding to clock, clock speed and bell drift, t_0 is the clock epoch reference epoch, Δt_i is the clock offset observation, v_i is the power law noise.

The accuracy of the clock-offset fitting model directly determines the accuracy of the clock model. When the data is collected, it is affected by the receiver failure or external interference, which causes the clock error observation data to be abnormal. Therefore, in order to reduce the impact of clock anomalies on fitting modeling, on the one hand, it is necessary to carry out the screening of outliers on the data of clock anomalies; on the other hand, the clock parameters estimation algorithm should have sufficient error suppression capability. The star clock parameters can be estimated using maximum likelihood or robust least squares.

- Whole network clock offset weighted estimation

Based on the sequence of clock offset observation excluding the abnormal values and the clock error forecasting after star clock modeling, the space information nodes are jointly estimated by the clock error. Specific steps include.

- (a) Obtain relative clock observations from inter-satellite relative measurements;
- (b) Pre-clock atomic clock offset X^* based on atomic clock model versus time base;
- (c) Define the true clock offset X , the clock offset error is $\delta X = X - X^*$;
- (d) Suppose L_u is the clock offset observation between satellite I and satellite j.

$$L_u = g_u(X_i, X_j) + n_u = |(X_i^* + \delta X_i) - (X_j^* + \delta X_j)| + n_u \tag{9}$$

Suppose the network nodes number is n, independent observation data is m, $m \leq C_n^2$.

The error formula is

$$V = H\delta X - l, l = L - HX^* \tag{10}$$

In the formula, $V_{m \times 1} = (v_1, v_2, \dots, v_m)^T$, $\delta X_{n \times 1} = (\delta X_1^T, \delta X_2^T, \dots, \delta X_n^T)^T$.

$$H = \begin{bmatrix} \dots & \dots & \dots & \dots & \dots \\ \dots & \left. \frac{\partial g_u}{\partial X_i} \right|_{(X_i^*, X_j^*)} & \dots & \left. \frac{\partial g_u}{\partial X_j} \right|_{(X_i^*, X_j^*)} & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \end{bmatrix} \tag{11}$$

Based on the Bayesian estimation principle, take the predicted atomic clock skew X^* as the prior information. The estimation error is

$$\delta \hat{X} = (H^T P_L H + P_X)^{-1} H^T P_L l \tag{12}$$

In the formula, $P_L = \text{diag}(\delta_0^2 / \delta_L^2)$ is the observation weight matrix, δ_0^2 is the mean error, and $P_X = \text{diag}(\delta_0^2 / \delta_X^2)$ is the predict clock offset weight matrix.

For the clock error observation data that satisfies the normal distribution, the Bayes estimation can get the optimal estimation result of the whole network clock error. However, if there is any abnormality or gross error in the observed value of the clock, then the robust M estimation method can be used. Construct the following criteria function

$$\Omega = \min \left[\sum_{i=1}^m \sum_{j=1}^m p_{L_{ij}} \rho(v_i, v_j) + \sum_{k=1}^g \sum_{h=1}^g p_{X_{kh}} \beta(\delta \hat{X}_k, \delta \hat{X}_h) \right] \tag{13}$$

$\rho(v_i, v_j)$ is the extreme function of measurement error, $\beta(\delta \hat{X}_k, \delta \hat{X}_h)$ is the extreme value function of the correction number.

Based on the criterion, make

$$\sum_{i=1}^m \sum_{j=1}^m p_{L_{ij}} \rho(v_i, v_j) + \sum_{k=1}^g \sum_{h=1}^g p_{X_{kh}} \beta(\delta \hat{X}_k, \delta \hat{X}_h) = 0$$

It also can be written as

$$\sum_{i=1}^m \sum_{j=1}^m h_i^T p_{L_{ij}} \phi(v_j) + \sum_{k=1}^g \sum_{h=1}^g e_k p_{X_{kj}} \eta(\delta \hat{X}_h) = 0 \tag{14}$$

h_i is the i row of coefficient matrix H , e_k is the k column of the unit matrix.

Make $\bar{p}_{X_{kh}} = p_{X_{kh}} \eta(\delta \hat{X}_h) / \delta \hat{X}_h$, $\bar{p}_{L_{ij}} = p_{L_{ij}} \phi(v_j) / v_j$.

Formula (14) can be written as

$$H^T \bar{P}_L V + \bar{P}_X \delta \hat{X} = 0 \tag{15}$$

Substitute the error equation $V = H\delta X - l$, the anti-error clock offset estimation is

$$\delta \hat{X} = (H^T \bar{P}_L H + \bar{P}_X)^{-1} H^T \bar{P}_L l \quad (16)$$

4 Algorithm simulation experiment verification

To verify the performance of the algorithm for simulation experiment design. In the experiment, a certain number of time nodes are used to construct the time alignment network. The network nodes obtain the clock atomic clock difference analog data based on the atomic clock skew difference method, time alignment is performed between the network nodes, and a certain amount of noise is added to characterize the comparison process Time alignment accuracy. By changing the network structure and comparing the measurement accuracy, different scenarios can be formed to verify the performance of the joint solution method of network clock error.

Simulate atomic clock and clock error data generation based on power model

$$x_i = x_{i-1} + \tau(y_i^{WP} + y_i^{WF} + y_i^{RW} + y_i^{FF}) + y_0\tau + \frac{1}{2}D\tau^2, \quad i = 1, 2, \dots, N \quad (17)$$

y_0 is the frequency drift rate; D is the linear frequency drift rate, for cesium clock and hydrogen clock, it is 0.

Cesium clock and rubidium clock analog data as shown in Figure 1. The rubidium clock frequency drift rate is taken as 10^{-12} , the linear drift rate is taken as 10^{-20} ; the frequency drift rate of cesium clock is taken as the same as rubidium clock. Based on the above configuration of parameters, the cumulative clock error of the rubidium clock was 10 ns at the same time, and the cumulative clock error of the cesium clock was ns. It can be seen that the cesium clock has better frequency stability than the rubidium clock.

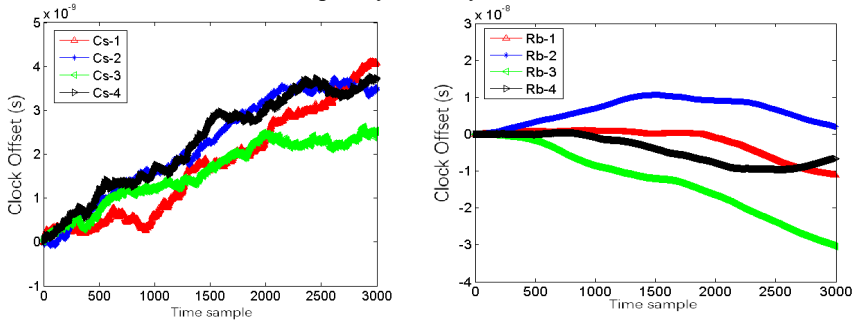


Fig. 1. Simulation of Atomic Clock Offset.

N -nodes are used to construct the clock difference observation network. Two way time comparison links are established between each other, and the number of the matching links is C_N^2 .

N is taken as 4, nodes are A, B, C, D respectively. Cesium clock model parameters is chosen for the node clock offset data simulation.

Experiment one: the whole network time comparison clock error estimation performance simulation

Suppose the accuracy of two way time alignment is assumed to be nanosecond, the number of matching links is six, and six sets of clock alignment data are obtained. Based on the cesium clock model described above, the clock error is modeled and predicted as the priori value.

Node clock error solution results shown in Figure 2.

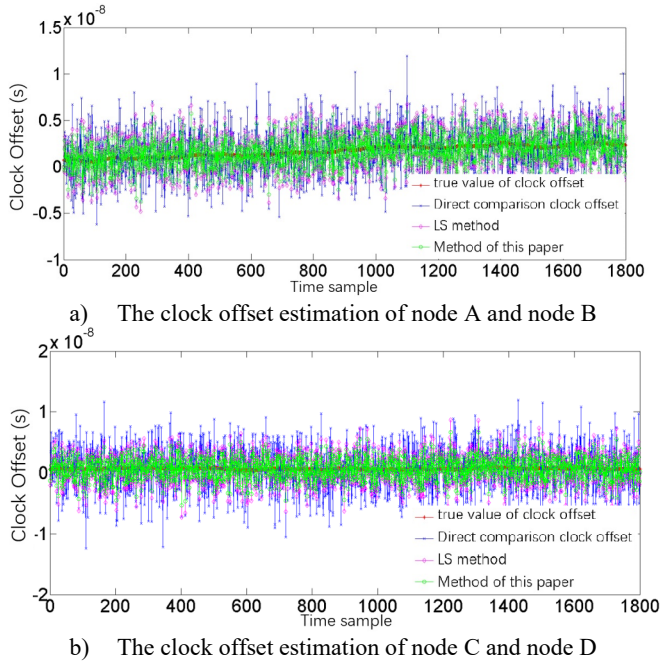


Fig. 2. Simulation of Clock Offset Resolution Performance.

The node clock error resolution and error root mean square (RMS) are shown in the following table.

Table 1. Clock offset resolution precision.

	Direct comparison of clock	Least square adjustment	This article method
A-B clock offset(s)	5.0518e-09	3.0029e-09	2.3815e-09
C-D clock offset(s)	3.5279e-09	2.6376e-09	2.1576e-09

Table 2. RMS of clock offset resolution.

	Direct comparison of clock	Least square adjustment	This article method
A-B clock offset(s)	5.0487e-09	3.0035e-09	2.3690e-09
C-D clock offset(s)	3.5094e-09	3.4762e-09	2.1301e-09

Experiment II: impact of measurement accuracy

Reduce the accuracy of the comparison link (standard deviation) of 10 nanoseconds, to carry out the same experiment, the experimental results shown in Fig 3. The experimental results show that the accuracy and accuracy of the error correction can still be improved based on the whole network adjustment algorithm under the condition that the ratio measurement is decreased. However, the precision of the error ratio is still affected by the accuracy of the comparison measurement.

Table 3. Performance of clock offset resolution.

A-B	Direct comparison of clock	Least square adjustment	This article method
Standard error of comparison error (s)	4.8975e-08	2.9184e-08	2.2831e-08

Mean square error of comparison (s)	3.5198e-08	2.5258e-08	2.0678e-08
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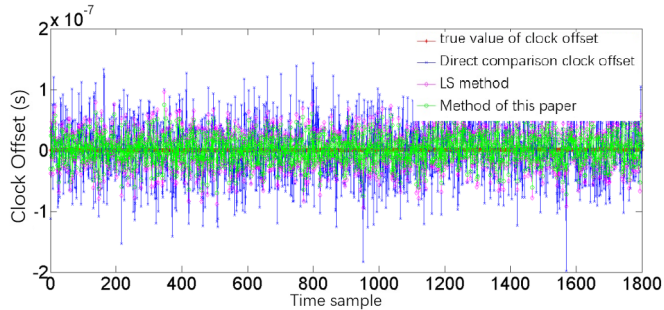


Fig. 3. Simulation of influence of measurement precision.

5 Conclusions

The satellite navigation systems represented by BeiDou and GPS all establish the measurement communication network based on the inter-satellite link. Based on the time alignment observation between the satellite and the ground nodes, the whole network clock error resolution strategy can be used to achieve higher Accuracy and stability of the entire network time synchronization. In this paper, aiming at the limitations of the traditional algorithms, taking the clock modeling as a priori value of clock error, we double weighted the clock error of the atomic clock and the comparison link to achieve better performance of the whole network clock error resolution compared with the traditional algorithm. The algorithm can be applied to the whole network time synchronization of satellite navigation system and also can be applied in the future construction of spatial information network covering all kinds of satellite systems in order to meet the requirements of the unified spatial and temporal reference of spatial information network and the coordination of multi-system tasks.

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