Analysis of BDS Satellite Clock Prediction Contribution to Rapid Orbit Recovery

Qian Chen, Junping Chen, Yize Zhang, Shan Wu and Xiuqiang Gong

Abstract The BDS-2 system is designed as a GEO/IGSO/MEO mixed constellation. Generally, there exists satellite maintaining operation for GEO or IGSO satellite every 7–10 days. During this period the maneuver satellite is out of service. It will be about 5–6 h starting from the beginning of satellite maneuver to the release of the first group of recovery orbit. Strategy of satellite clock assisted precise orbit determination (POD) is normally implement, where the most critical factor that contributes to the availability of maneuver satellites is the length of accumulation of data. However, the last hour of real-time observed pseudo-range data of tracking station could not be included in POD, due to the reason that the satellite clock could not be observed in real-time. In this paper, we propose to use the polynomial fitting method to forecast the satellite clocks and use it in POD. We analyze the accuracy of satellite clocks prediction and its contribution to the rapid orbit recovery. Results show that the satellite unavailability time could be shortened by at least 1 h, which effectively improves satellite availability. And it improves the accuracy of orbit determination and prediction by more than 15 and 70%.

Keywords BDS · Time synchronization · Satellite clock · Precise orbit determination · Rapid orbit recovery · Satellite availability

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1 Introduction

The Global Navigation Satellite System (GNSS) provides important spatiotemporal information and plays an increasingly prominent role in social life. Precise Orbit Determination (POD) and prediction are one of the important processes for GNSS PNT (Positioning, Navigation and Timing) service [1, 2]. Among different methods, multi-satellite orbit determination and prediction using data of 3–7 days are widely used [3]. Due to various perturbations on the satellites, orbit maneuver control is required to maintain satellite constellation configuration [4]. During the orbit maneuver periods, the satellite dynamics is normally different from previous arcs. Thus, strategies have to be developed for the fast orbit recovery to support the recovery of satellite availability, which is the key factor in the GNSS applications of life safety, such as aviation etc. [5].

BDS' constellation is composed of GEO/IGSO/MEO satellites. The unique system design makes the satellite maneuver more frequently. Every 7–10 days there will be a GEO or IGSO satellite under orbit control operation, during which the maneuver satellite is unavailable. During the period of maneuver, tracking data has to be re-accumulated for POD, as the orbit dynamics change. In this period, strategy of satellite clock assisted POD is developed [4, 6, 7], where the satellite clocks and station clocks from the technique of Two Way Time Transfer (TWTT) are normally used as known parameters in the POD process. It may take 5–6 h starting from the beginning of orbit control until the first group of rapid recovered orbit is released.

This paper studies the strategy to shorten the satellite maneuver period. As discussed previously, the clocks from TWTT is the key parameters in the fast POD process. However, the TWTT technique is normally in post-processing with latency of around 1–2 h. To make the first group of recovered orbit released earlier, we propose to use a polynomial fitting method to forecast the satellite clocks from TWTT technique. The accuracy of predicted satellite clocks and its contribution in satellite clock assisted POD is discussed.

2 Methods of Rapid Orbit Recovery and Clock Processing

Conventional POD use longer arcs using data of 3–7 days for multi-satellite orbit determination, but the orbit dynamics are changed during the satellite maneuver periods. In order to recover satellite orbit as soon as possible, short arcs are used to improve orbit accuracy and system availability [8].

2.1 Dynamic Model

Satellites suffer from a variety of forces during the rotation around the earth. The dynamic model used in orbit determination is as the following:

$$F = f_{TB} + f_{NB} + f_{NS} + f_{TD} + f_{RL} + f_{SR} + f_{AL} \quad (1)$$

where f_{TB} is the gravity of the earth on the satellite, f_{NB} is the N-body perturbation, f_{NS} is the non-spherical gravitation perturbation of the earth, f_{TD} is the solid tide and ocean tide perturbation, f_{RL} is the relativistic perturbation, f_{SR} is the solar pressure, and f_{AL} is the Earth's albedo radiation Pressure perturbation (Table 1).

2.2 Observation Model

Rapid orbit recovery use pseudo-range observations of a tracking network. The pseudo-range observation equation is as the following [9, 10]:

$$\begin{aligned}\rho_j^i = {} & \sqrt{(x^i - x_j)^2 + (y^i - y_j)^2 + (y^i - y_j)^2} + c \cdot dt_j \\ & - c \cdot dt^i + \delta_{trop} + \delta_{ion} + \delta_{rel} + \varepsilon\end{aligned} \quad (2)$$

where (x^i, y^i, z^i) is the satellite position, (x_j, y_j, z_j) is the station location, dt_j is the station clock error, dt_i is the satellite clock error, δ_{trop} is the tropospheric correction, δ_{ion} is Ionospheric correction, δ_{rel} stands for relativistic correction, and ε is the multipath effects and other kinds of noise.

The location of the station are normally accurately determined previously and the tropospheric and ionospheric errors can be corrected by the model. Technique of carrier phase smoothing pseudo-range is applied here to obtain higher precision pseudo-range observation.

2.3 Satellite Clock Error Prediction Model

The clock accuracy in the satellite clock assisted POD should be better than 0.5 ns [11].

As satellite clock from TWTT is not broadcasted in real-time, only the clock parameters of previous hours could be used in rapid orbit recovery. To realize

Table 1 Model description

	Model
The gravity of the earth's gravity center	10 × 10 JGM-3 model
N body perturbation	Sun and moon gravity perturbation
Planetary calendar	JPL DE403
Nutation model	IAU80 model
Solid tide	IERS96 model
Solar pressure and earth's albedo radiation pressure	Box-wing model

real-time processes, the quadratic polynomial model could be used to fit and predict the satellite clocks, the model can be modeled as the following:

$$T_i = a_0 + a_1(t_i - t_0) + a_2(t_i - t_0)^2 \quad (3)$$

where t_0 is the reference time, t_i is the user epoch, (a_0, a_1, a_2) are the constant, linear and acceleration terms of satellite clocks, which can estimated from least square estimation [12–14].

Assuming that the clock error with respect to time t_i is x_i and the observation error is v_i, we can establish the error equation:

$$x_i + v_i = a_0 + a_1(t_i - t_0) + a_2(t_i - t_0)^2$$

Setting $\hat{a} = [\hat{a}_0, \hat{a}_1, \hat{a}_2]^T$ as (a_0, a_1, a_2) estimates, the coefficient matrix is as the following:

$$A = \begin{bmatrix} 1 & (t_1 - t_0) & (t_1 - t_0)^2 \\ 1 & (t_2 - t_0) & (t_2 - t_0)^2 \\ \cdots & \cdots & \cdots \\ 1 & (t_i - t_0) & (t_i - t_0)^2 \end{bmatrix}, \quad L = \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_i \end{bmatrix}$$

And it could be estimated by the equation: $\hat{a} = (A^T A)^{-1} A^T L$.

3 Analysis of Rapid Orbit Recovery

3.1 Orbit Determination Strategy

Satellite clock assisted POD strategy is applied for rapid orbit recovery. The station clocks can be retrieved from the multi-satellite POD, while the satellite clocks estimation include two parts: the satellite clocks can be corrected directly for the arc using the TWTT technique, and predicted when there is no TWTT satellite clocks in the last hour. The pseudo-range data can be smoothed using carrier phase data to reduce pseudo-range noise and multipath effect in data preprocessing.

Figure 1 shows the different data accumulation processes during rapid orbit recovery, where t_0 is the epoch when the orbit control is terminated and the start of data re-accumulation, t is the current epoch. From the figure we see that the accumulation of satellite clock data are late than the observation, due to the latency of TWTT process.

We define two types of processing methods of POD for comparison and analysis.

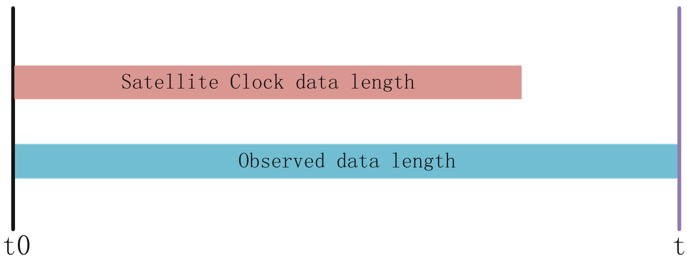

Fig. 1 Rapid orbit recovery of data accumulation diagram

Strategy 1: Only use the observed TWTT clocks and re-accumulated observations in POD.

Strategy 2: TWTT observed and predicted satellite clocks are both used, which can make full use of the observed data.

3.2 Introduction of Experiment Data

Data of 7 tracking stations evenly distributed in China are used, which is shown in Fig. 2. Three periods where GEO satellites experienced maneuver in October 2017 are selected for the experiment. The maneuvering information is shown in Table 2.

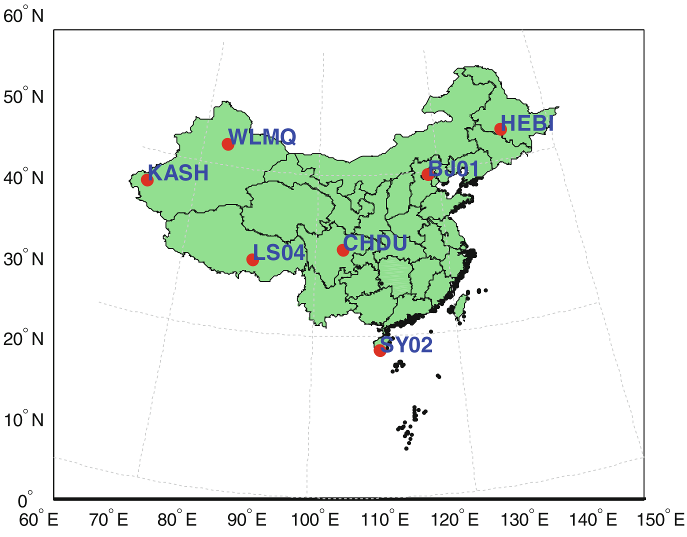

Fig. 2 Selected stations

Table 2 Satellite maneuvering information

SatID	Start time	End time	Available time
C01	2017-10-31 8:55	2017-10-31 10:15	4 h after maneuver
C02	2017-10-19 8:59	2017-10-19 11:15	4 h after maneuver
C03	2017-10-23 8:46	2017-10-23 11:15	4 h after maneuver

3.3 Analysis of Experiment Results

Firstly, the satellite clocks fitting and prediction accuracy is analyzed. The fitting accuracy of 1-h interval is within 0.3 ns and clock prediction errors is below 1.5 ns, which can be concluded from Table 3.

Using data spanning from 3 to 8 h, POD are carried out 6 using strategy 1 and strategy 2. With the observation data from The POD residuals, UERE and UERE after 1 h prediction are assessed, as shown in Table 4 and Figs. 3 and 4, respectively.

Table 3 Accuracy of fitting and predicted satellite clock for 1 h (unit: ns)

SatID	Accuracy	Predicted 1 h
C01	0.11	0.81
C02	0.09	0.80
C03	0.06	0.78
C04	0.11	1.14
C05	0.07	0.93
C06	0.24	1.23
C07	0.23	1.30
C08	0.17	1.33
C09	0.21	1.41
C10	0.26	1.44

Table 4 Residuals of orbit determination (unit: m)

SatID (h)	C01		C02		C03	
	Strategy 1	Strategy 2	Strategy 1	Strategy 2	Strategy 1	Strategy 2
3	1.120	1.070	0.631	0.688	0.524	0.516
4	1.070	0.961	0.682	0.679	0.513	0.521
5	0.962	0.608	0.677	0.678	0.522	0.509
6	0.610	0.641	0.676	0.642	0.509	0.495
7	0.611	0.582	0.641	0.650	0.496	0.490
8	0.585	0.621	0.652	0.679	0.492	0.512

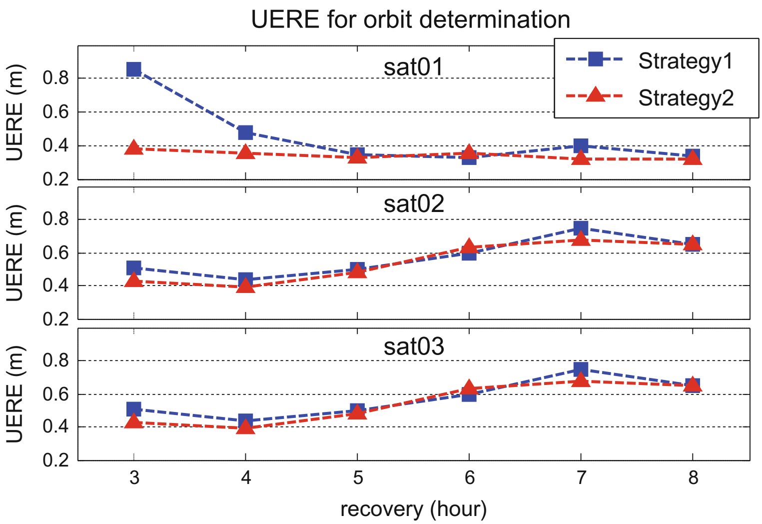

Fig. 3 UERE of each satellite during rapid orbit recovery

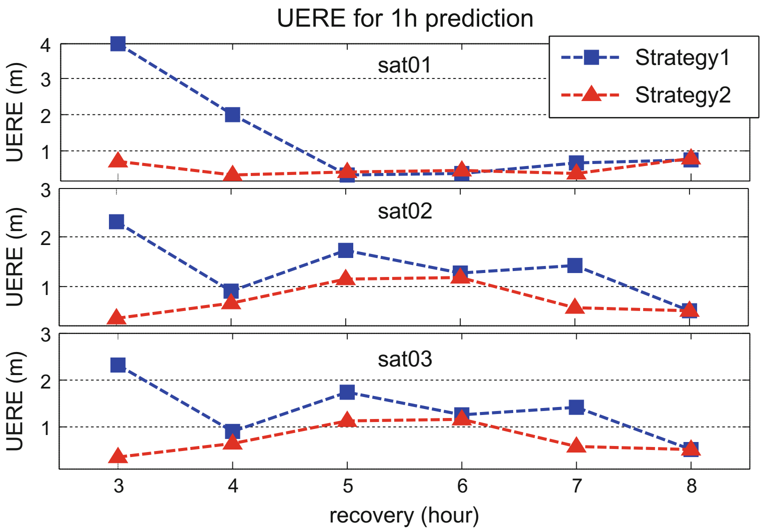

Fig. 4 UERE after 1 h prediction of each satellite during rapid orbit recovery

From the result we can see that the POD residuals of the two strategies are about 0.6 m, the differences is at millimeter level.

As for UERE results, the prediction accuracy of 3 h for strategy 1 is 1.9–3.9 m, while it is less than 1 m for strategy 2. This may due to the inclusion of more observation data, where satellite clocks are predicted. According to the Fig. 4, the

Table 5 Statistics of orbit determination (unit: m)

SatID	Time (h)	Orbit determination UERE			Forecast for 1 h UERE		
		Strategy 1	Strategy 2	Improvement (%)	Strategy 1	Strategy 2	Improvement (%)
C01	3	0.856	0.378	55.848	3.982	0.717	81.996
	4	0.476	0.354	25.672	1.997	0.341	82.919
	5	0.341	0.326	4.368	0.367	0.435	−18.484
	6	0.331	0.352	−6.377	0.400	0.486	−21.600
	7	0.402	0.323	19.497	0.697	0.376	46.114
	8	0.336	0.320	4.911	0.744	0.819	−10.052
C02	3	0.505	0.423	16.261	2.308	0.338	85.369
	4	0.436	0.394	9.529	0.889	0.632	28.941
	5	0.502	0.483	3.845	1.733	1.130	34.785
	6	0.600	0.628	−4.600	1.251	1.163	7.049
	7	0.750	0.679	9.433	1.415	0.564	60.158
	8	0.647	0.650	−0.526	0.502	0.501	0.179
C03	3	0.801	0.673	15.980	1.929	0.568	70.561
	4	0.670	0.680	−1.462	0.503	0.502	0.219
	5	0.683	0.643	5.801	0.842	0.546	35.139
	6	0.645	0.672	−4.169	0.506	0.476	5.873
	7	0.638	0.638	−0.063	0.494	0.513	−3.742
	8	0.611	0.614	−0.541	0.461	0.463	−0.456
Mean		**0.568**	**0.513**	**8.523**	**1.168**	**0.587**	**26.943**

POD precision and prediction accuracy of the strategy 2 is more stable, especially during the first few hours. The contribution to the orbit prediction for strategy 2 gradually decreases over time as more data are accumulated. The detailed comparison of strategy 1 and strategy 2 is listed in Table 5.

According to the statistics of the experiment results, it can be seen that the satellite clock prediction contributes the most to the first few hours where very few data are available. It improves orbit determination accuracy by more than 15% and over 70% on orbit prediction accuracy.

4 Conclusions

The accuracy of orbit determination during satellite orbit recovery is mainly limited by the amount of observation data. However, with the increase of the observation length, the orbit accuracy is mainly limited by the model accuracy and the quality of observed data. Aiming at reducing the recovery time after satellite's maneuver, we propose a method to use the predicted satellite clocks in POD. By using quadratic polynomials, the accuracy of short-term prediction is better than 0.3 ns. The contribution of predicted satellite clocks to orbit determination and prediction is particularly significant during the first few hours of rapid orbit recovery. The contribution to orbit determination accuracy is above 15% and the contribution of orbit prediction accuracy is more than 70%. The optimization strategy can shorten the satellite unavailable period by at least one hour during satellite maneuvering, which would benefit the system service.

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