Research on Reducing the Periodic Fluctuation of GEO Satellite One-way Timing Deviation

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Abstract. The satellite timing service has been used widely for its high precision and low cost. Based on the periodic fluctuation of the GEO satellite one-way timing deviation, this paper explores the relationship between the phenomenon and satellite movement, and then found a very strong linear correlativity between timing deviation and signal transmission delay difference. Therefore, this paper proposes a linear delay contribution compensation model in order to reduce the cyclical influence of timing deviation. The experimental result proves that the model can modify the original timing result at most 70% and almost eliminate the periodic fluctuations.

1. Introduction
Timing refers to a series of work that determines and maintains a certain time scale, and transmits time information representing this scale to users in various ways[1]. The operation of mobile communication networks, power system networks, financial networks, etc. needs continuous and accurate time. At present, most timing methods are based on radio broadcasting, which are divided into short-wave timing, long-wave timing, satellite timing, Internet timing, and telephone timing, etc. Among them, due to high accuracy and low cost, satellite timing has a broad development prospect [2].

Geosynchronous orbit satellites(GEO) have important applications in the BeiDou Navigation Satellite System (BDS), which can provide positioning, navigation, short message communication and other services, in addition, it can also provide high-precision one-way timing service [3-4].

Through monitoring, it was found that the results of GEO satellite one-way timing service have periodic fluctuations[5]. People have conducted extensive research on this phenomenon, and studied the system modification to reduce the impact[6], and refined the algorithm of the signal transmission time[7], etc. But there is no relevant research on improving the user algorithm to reduce the impact. This paper studies the factors related to the periodic fluctuations of the one-way timing, and proposes a model that can reduce the impact on the receiver. Experiment result shows that the model can effectively reduce the timing deviation and improve the timing accuracy.

2. GEO satellite one-way timing principle
The ground station sends the time reference signal to the GEO satellite, and the satellite transponder transmits the time signal to the user. The user terminal demodulates the reference time scale of the time signal, calculates the time interval between the local time and the reference time. The propagation delay of the time signal is calculated by parameters such as time delay, satellite coordinates and ionosphere. Adjust the local time according to the time interval and propagation delay, and complete the GEO satellite one-way timing service [8-10].
As shown in figure 1, $t_0$ is the transmitting time, $t_k$ is the time when the time signal leaves the ground station, $t_{sr}$ is the satellite receiving time, $t_{ss}$ is the satellite transmitting time, $t_{ur}$ is the time when the signal reaches the user, $t_u$ is the user using time, $\delta_1$ is the ground equipment delay, $\delta_2$ is the satellite equipment delay, $\delta_3$ is the user equipment delay, $\delta_{up}$ is the signal uplink transmission delay, including uplink delay and uplink delay correction, and $\delta_{down}$ is the signal downlink transmission delay, including downlink delay and downlink delay correction. The relationship between the parameters is shown in formula (1)-(5).

$$t_k = t_0 + \delta_1$$  \hspace{1cm} (1)  

$$t_u = t_k + \delta_{up} = t_k + \tau_{up} + \eta_{up} = t_k + \sqrt{(x_u - x_k)^2 + (y_u - y_k)^2 + (z_u - z_k)^2} / c + \eta_{up}$$  \hspace{1cm} (2)  

$$t_{ss} = t_u + \delta_2$$  \hspace{1cm} (3)  

$$t_{ur} = t_{ss} + \delta_{down} = t_{ss} + \tau_{down} + \eta_{down} = t_{ss} + \sqrt{(x_{ur} - x_{ss})^2 + (y_{ur} - y_{ss})^2 + (z_{ur} - z_{ss})^2} / c + \eta_{down}$$  \hspace{1cm} (4)  

$$t_u = t_{ur} + \delta_3$$  \hspace{1cm} (5)  

Where: $\tau_{up}$ is the uplink delay; $\tau_{down}$ is the downlink delay; $\eta_{up}$ is the uplink delay correction (including uplink ionospheric and tropospheric delay, etc.); $\eta_{down}$ is the downlink delay correction (including downlink ionospheric and tropospheric delay, etc.); $(x_0, y_0, z_0)$ is the ground antenna phase center coordinates; $(x_u, y_u, z_u)$ is the user antenna coordinates; $(x_{sr}, y_{sr}, z_{sr})$ is the satellite position of the receiving time; $(x_{ss}, y_{ss}, z_{ss})$ is the satellite position of the transmitting time. Among them, the "transmission time" is measured by the ground station, the uplink delay is given in navigation message or fitting, the downlink delay is determined by the distance of the satellite and user's position, and other corrections are determined by the parameters given in navigation message. At the same time, the forward delay is defined as the sum of the uplink delay and the downlink delay.

3. Timing monitor and analysis

3.1. Timing monitor

The user terminal gets the time from the satellites, and compares it with the reference time, and complete the monitoring. We made long-term monitoring of the one-way timing of different GEO satellites in Beijing, Sanya and Chengdu (as shown in figure 2), and found that the timing deviation have phenomenon of periodic fluctuations, but the deviation are within 50ns [11-14].
Monitoring the timing deviation of GEO satellite orbit control before and after (as shown in Figure 3), and found that after orbit control, the timing deviation are significantly better. (The position of the satellite is in the CGCS2000 coordinate system, and the z-direction is pointing from the South Pole to the North Pole)

According to the monitoring, it is found that the position and movement speed of the satellite in the z-direction are strongly correlated with the periodic fluctuations of the timing deviation. During the movement of the satellite from the equator to the north and south ends, the speed in the z-direction gradually decreases, the acceleration gradually increases, and the timing deviation gradually decreases; when the satellite moves to the north and south ends, the z-direction speed is zero, the acceleration is the largest, and the timing deviation is the smallest; during the movement of the satellite from the north and south ends to the equator, the speed in the z-direction gradually increases, the acceleration gradually decreases, and the timing deviation gradually increases; when the satellite moves above the equator, the z-direction speed is the largest, the acceleration is zero, and the timing deviation is the
largest; when the satellite moves to the north and south ends, the smaller the inclination from the equatorial plane, the smaller the timing deviation [5].

3.2. **Analysis of fluctuation law of timing deviation**

The main factors for the periodic fluctuation of the timing deviation are satellite ephemeris forecast errors, uplink delay errors, forwarding time errors, etc., which are closely related to the movement characteristics of GEO satellites; at the same time, satellite ephemeris forecast errors will also affect the uplink delay, forwarding time and downlink delay [15-16]. Since the delay directly obtained by the receiver is uplink delay and forward delay, and the downlink delay is calculated indirectly. As is shown in figure 4 and 5, when the uplink/forward delay is maximum (minimum), the timing deviation is minimum. By making a difference to the uplink/forward delay, there is an approximately linear relationship between the timing deviation and the uplink/forward delay difference.

![Figure 4. Contrast Timing Deviation with uplink Delay Difference](image1)

![Figure 5. Contrast Timing Deviation with forward Delay Difference](image2)

The forward delay and the uplink delay can be used to calculate the downlink delay. Therefore, the timing deviation is also linearly related to the downlink delay difference.

4. **Modified Model for Periodic Fluctuation of Time Deviation**

4.1. **Delay contribution compensation model**

Since the timing deviation is linearly related to the difference of uplink and downlink delay, the impact of the uplink and downlink delay on the periodic fluctuations of the timing deviation are regarded as "contribution", which is analyzed to compensate for the uplink and downlink delay. Establish a linear delay contribution compensation model, see equation (6):
\[ M(t) = k_1 \times t_{\text{upc}}(t) + k_2 \times t_{\text{downc}}(t) \]  

(6)

Where: \( M(t) \) is the delay compensation at \( t \); \( k_1 \) is the uplink delay contribution compensation coefficient; \( t_{\text{upc}}(t) \) is the uplink delay difference at \( t \); \( k_2 \) is the downlink delay contribution compensation coefficient; \( t_{\text{downc}}(t) \) is the downlink delay difference at \( t \). Among them, \( t_{\text{upc}}(t) \) and \( t_{\text{downc}}(t) \) can be obtained by processing the broadcast message information and can be regarded as a known quantity. Therefore, the delay compensation can be calculated only by determining the compensation coefficient in the formula.

4.2. Influencing factors of delay contribution compensation coefficient

The correlation analysis method is used to analyze the effects of receiver position, satellite orbit inclination, and different satellites on time delay contribution compensation coefficients.

4.2.1. Effect of receiver position on delay contribution compensation coefficient

Uplink delay refers to the delay generated when the signal is transmitted from the ground to the satellite. It is irrelevant to the receiver position, that is, the uplink path is uniform for users at different locations on the same satellite and at the same time, and the uplink delay is determined. Then, the "contribution" of the uplink delay to the timing deviation is certain. Therefore, the receiver position has no effect on the uplink delay contribution compensation coefficient.

Downlink delay refers to the delay generated when the signal is transmitted from the satellite to the receiver. It is related to the receiver position, that is, the downlink path is different for the users at different locations on the same satellite and at the same time. Then, the "contribution" of the downlink delay to the timing deviation of the timing results is also different, as shown in figure 6. Therefore, the receiver position has an impact on the downlink delay contribution compensation coefficient.

4.2.2. Effect of satellite orbit inclination on delay contribution compensation coefficient

As shown in figure 7, where figure (a) is the relationship between timing deviation and forward delay difference before orbit control, the linear fitting slope is 0.6; figure (b) is the relationship between timing results and positive delay difference after orbit control, the linear fitting slope is 0.6. The timing deviation and forward delay difference are in a proportional linear relationship before and after the orbit control. Therefore, the satellite orbit inclination has no effect on delay contribution compensation coefficient.
4.2.3. Effect of different satellites on the delay contribution compensation coefficient

As shown in Figure 8, where figure (a) is the relationship between the GEO-1’s timing deviation and uplink/downlink delay difference, the linear fitting slopes are 0.8; figure (b) is the relationship between the GEO-2’s timing deviation and uplink/downlink delay difference, the linear fitting slopes are 1.4. Therefore, different satellites have an influence on the delay contribution compensation coefficient.

Above all, the uplink delay contribution compensation coefficient is only related to satellites and the downlink delay contribution compensation coefficient is related to satellites and receiver positions.

4.3. Calculation of time delay contribution compensation coefficient

4.3.1. Linear regression model

A univariate linear regression model is used for the timing deviation-uplink/downlink delay difference, see equation (7):

\[ NT = NT_{up} + NT_{down} \]
\[ NT_{up} = k_1 \cdot T_{up} + E_{up} \]
\[ NT_{down} = k_2 \cdot T_{down} + E_{down} \]  

(7)

Where: \( NT = [n_t_1, n_t_2, \cdots, n_t_n] \) is the timing deviation matrix; \( NT_{up} = [n_{t_{up1}}, n_{t_{up2}}, \cdots, n_{t_{upn}}] \) is the uplink deviation matrix; \( NT_{down} = [n_{t_{down1}}, n_{t_{down2}}, \cdots, n_{t_{downn}}] \) is the downlink deviation matrix; \( T_{up} = [t_{up1}, t_{up2}, \cdots, t_{upn}] \) is the uplink delay difference matrix; \( T_{down} = [t_{down1}, t_{down2}, \cdots, t_{downn}] \) is the downlink delay difference matrix; \( k_1 \) is the uplink delay contribution compensation coefficient; \( k_2 \) is downlink delay contribution.
compensation coefficient, \(k_1\) and \(k_2\) constitute the regression coefficient of the model; \(E = [e_1, e_2, \ldots, e_n]\) is the random variable of independence that has zero mean and \(\sigma^2\) variance.

### 4.3.2. Compensation coefficient estimation

The least square method is used to estimate the compensation coefficient with the following relationship:

\[
\begin{align*}
Q_{\min}(k_i) &= \min_{k_i} Q(k_i) = \min_{k_i} \sum_{j} e_{\text{up}}^2 \quad (7) \\
Q_{\text{down}}(k_i) &= \min_{k_i} Q(k_i) = \min_{k_i} \sum_{j} e_{\text{down}}^2 \quad (8)
\end{align*}
\]

For GEO satellites 36,000km above the equator and users in Beijing, the signal uplink and downlink processes are almost symmetrical.

As shown in figure 9, where figure(a) is the fitting diagram of timing deviation and uplink delay difference of GEO-1 satellite in Beijing, and the linear fitting slopes are 0.8, so \(k_1 = k_2 = 0.4\); figure(b) is the fitting diagram of timing deviation and uplink delay difference of GEO-2 satellite in Beijing, and the linear fitting slopes are 1.4, so \(k_1 = k_2 = 0.7\).

In other locations except Beijing, \(k_2\) can be obtained by substituting \(k_1\) into formula (7) and (8). According to this, \(k_2 = 0.2\) in Chengdu for GEO-1 and \(k_2 = 1.4\) in Sanya for GEO-2.

### 5. Experiment

Comparing the timing deviations directly from the receiver and after the delay contribution compensation model processing, using standard deviation for statistics.

The experiment selects multiple sets of data, the selection principle avoids the data used in the above analysis process as much as possible, and adds a set of real-time processing data. The experimental results are shown in figure 10.
Table 1. Experimental evaluation results

| Sources        | Original standard deviation | Modified standard deviation | Increase rate |
|----------------|-----------------------------|-----------------------------|---------------|
| GEO-1 Beijing  | 18.4958                     | 6.8239                      | 63.1%         |
| GEO-2 Beijing  | 19.1151                     | 5.9030                      | 69.1%         |
| GEO-2 Sanya    | 10.8809                     | 7.4534                      | 31.5%         |
| GEO-1 Chengdu  | 12.4929                     | 5.3733                      | 57.0%         |

From the results, it can be seen that the modified standard deviation of the timing deviation of various satellites in multiple places is between 5ns and 8ns, the correction range is above 30%, the highest correction range is nearly 70%. The periodic fluctuations are reduced clearly and timing deviation has been improved greatly.

6. Conclusion
The periodic fluctuations of the timing deviation of GEO satellites are regular. The fluctuations are related to the speed of the satellite in the z-direction during the movement, and are linearly related to the difference of the uplink delay and the positive delay. Through the analysis of the above linear correlation, based on the uplink and downlink delay difference and the delay contribution compensation coefficient, a delay linear contribution compensation model is established. It has been verified that this model can improve the timing accuracy greatly.

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