A High Precision Satellite Beam Agility Control Method

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Abstract. This paper proposes a high precision satellite beam agility control system that accounts for the satellite-ground time delay error caused by the rotation of the Earth. It is aimed to achieve high precision beam hopping of the phased array with sub-millisecond time granularity between multiple ground terminals in satellite communication. This system integrates a highly stable clock with a global navigation system to optimally calculate the satellite-ground transmission delay, correcting the orbital position through a two-iteration process. Simulation results show that the method can further improve the estimation accuracy of the satellite ground signal transmission delay under the satellite computationally constrained conditions. It achieves high time synchronization of the satellite-ground communication beam time and improves the efficiency of satellite-ground communication.

Keywords: Satellite Beam Agility control · Time Delay Compensation · High Time Synchronization

1 Introduction

Research on satellite Internet and its key technologies has created a worldwide research boom in academia and industry. Onboard multibeam phased array antenna technology is widely recognized as a core key technology for improving the performance of low orbit satellite communication systems. However, traditional low orbit satellites mostly use fixed beam coverage, and the total available frequency band of the system is multiplexed in all beams according to a certain multiplexing factor, which results in low spectral efficiency [1–4]. This fixed communication resource sharing mechanism will restrict the service capability of space Internet based on low orbit satellite constellations, making it difficult to meet the communication needs of the proliferation of the number of service users, data volume, and types of services of low orbit satellite constellations. It is a bottleneck technical problem restricting the development of space multimedia Internet. The hopping beam coverage technology of satellite-carried multibeam phased

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array antenna is a real-time adjustment of the beam service object for the current communication demand of the active users under the satellite taking into account the system throughput under the constraints of system resources and service fairness. This technology can not only reduce inter-beam interference and improve spectrum utilization and system trigger capacity, but also use fewer beam to achieve the same coverage effect as more fixed beams, thus improving satellite resource efficiency [5].

For a beam hopping system, the onboard beam switches between multiple ground terminals at a sub-millisecond time granularity, while the signal transmission delay between the satellite and the ground varies between 0 to 10 ms. Therefore, it is necessary to accurately adjust the beam hopping time on the satellite, fully considering the satellite-ground transmission delay and clock errors, to ensure that the beams transmitted by the satellite can be accurately received by the ground terminals even after sub-millisecond level hopping and millisecond level spatial transmission. Similarly, the signals transmitted by the ground terminals can still be accurately received by the receiving beam on the satellite even after sub-millisecond level hopping and millisecond level transmission [6].

There are not many domestic and foreign reports of hopping-beam based real-time communication system related technologies being applied on low orbit satellites. There is no reference system protocol for the management and control of satellite-ground communication resources under this system. The research on core key technologies and engineering practicality needs to be deepened urgently [7]. The general method of calculating the satellite-ground delay is to use the satellite's ephemeris to obtain the coordinate information of the satellite position and the coordinate information of the ground station to calculate the Euclidean distance divided by the speed of light. However, this method ignores the factor of the rotation of the Earth, and the obtained satellite-ground transmission delay causes errors. This paper proposes a method for satellite communication beam hopping control using a highly stable onboard clock and a global navigation system to achieve time synchronization. It improves the control accuracy of the phased-array beam agility time and achieves the alignment of the onboard beam hopping time to the ground terminal time.

2 Design of Beam Agility Control System

The satellite communication beam agility control system for time synchronization is shown in Fig. 1. It's supposed that the beam hopping requires alignment to the hop time T_0 of the ground communication system's time system. For downlink communication, it is required to generate an onboard transmitting beam hopping control pulse, the time of which must ensure that the signal is transmitted to the ground terminal through the transmitting beam of the phased array at the moment of T_0. For uplink communication, it is required to generate an onboard receiving beam hopping control pulse, the time of which must ensure that the signal transmitted from the ground station at time T_0 can be accurately received by the phased array receive beam after space transmission. This system consists of a phased array antenna, a beam agility control pulse generation module, a beam agility time calculation module, a time maintenance module, and a GNSS (Global Navigation Satellite System) receiver.

The GNSS receiver obtains the satellite's orbital position in the WGS-84 coordinate system by receiving navigation satellite signals and decoding the navigation message.

It sends the current onboard time t and the corresponding satellite orbital position $B(t) = (X_B, Y_B, Z_B)$ to the beam agility control pulse generation module every second, and outputs a 1 Hz pulse to the time maintenance module every second. The rising edge of the 1 Hz pulse is aligned to the navigation system time.

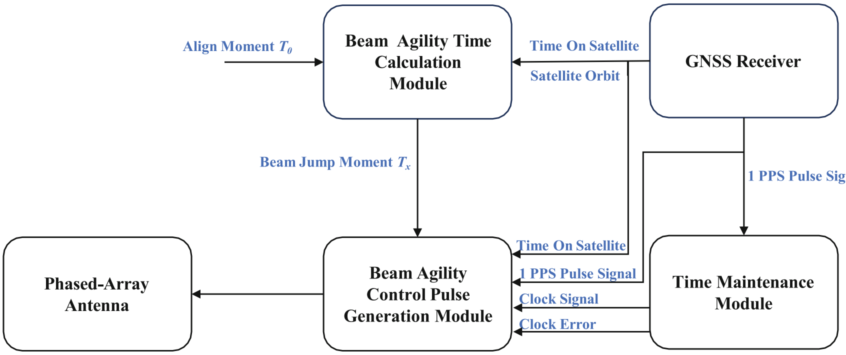

Fig. 1. Design of beam agility control system for satellite communication

The time maintenance module has a highly stable local indicator clock with a frequency of 100 MHz, but the clock accuracy does not meet the time control requirements. The clock error needs to be obtained based on the exact 1 s duration output from the GNSS. When the rising edge of each second pulse arrives, it starts counting based on the local clock until the rising edge of the next second pulse arrives. The count of the t th second is N_t, and the local clock error is E after accumulating W seconds. The time maintenance module sends the local clock error E to the beam agility control pulse generation module. E can be determined by

$$E = \frac{1}{W}\sum_{t=1}^{W}\left(10^8 - N_t\right) \tag{1}$$

The beam agility time calculation module calculates the signal space transmission delay according to the beam agility time T_0 aligned to the ground communication system annotated on the ground operation and control system, the position of the ground station $A(t) = (X_A, Y_A, Z_A)$, and the orbit $B(t) = (X_B, Y_B, Z_B)$ of the satellite at the time t. The beam agility time calculation module calculates the onboard beam hopping time to meet the signal hopping time alignment to the ground time. Finally, the beam agility time calculation module sends the onboard beam hopping time T_x to the beam agility control pulse generation module.

3 Time Delay Theory Analysis and Compensation Methods

3.1 Time Delay Theory Analysis

The satellite dynamically calculates the time delay according to the satellite-ground distance change and aligns the ground-based base station time slots to each time slot. The actual start time of each time slot is delayed in uplink communication and advanced in downlink communication. This paper analyses the uplink communication scenario.

The beam hopping time T_x is determined by the following four variables: (1) The time in the beam hopping table, which is the ground base station signal transmission time T_0. (2) The signal transmission delay from the ground base station to the ground feeder antenna interface T_1. (3) The signal transmission delay through the air interface T_2. (4) The signal transmission delay from the satellite feeder antenna to the phased array antenna T_3. The relationship between them is as follows:

$$T_x = T_0 + T_1 + T_2 + T_3 \tag{2}$$

This paper completes the error compensation of the transmission delay T_2 due to the rotation of the Earth. Suppose the delay is calculated directly using the orbit at the moment of signal initiation. In that case, the signal space transmission delay is calculated using the position of the ground station $A(t) = (X_A, Y_A, Z_A)$, and the satellite's orbit $B(t) = (X_B, Y_B, Z_B)$ at the moment *t*. Signal space transmission $T_2{}'$ delay can be determined by

$$T_{2'} = \frac{\sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2 + (Z_B - Z_A)^2}}{c} \tag{3}$$

where c denotes the speed of light, is $3*10^8$ m/s. If the maximum speed of the satellite is v m/s, then the maximum position error Δ_p during transmission time can be determined by

$$\Delta_p = v * T_2' \tag{4}$$

Then the corresponding time delay error Δ_t can be determined by

$$\Delta_t = \frac{\Delta_p}{c} \tag{5}$$

3.2 Time Delay Compensation Methods

For uplink communication, the base station sends a signal at the moment T_0, which can be accurately received by the beam of the receiving phased array after spatial transmission, and the time at which the signal is received is T_x.

The WGS-84 coordinate of the satellite at T_0 is $B(T_0) = (X_B(T_0), Y_B(T_0), Z_B(T_0))$. Due to the limitation of computational resources, it is necessary to linearly interpolate the orbit to compensate the orbit error for the signal transmission delay T_1 from the ground base station to the ground feed antenna. The corrected orbit is $B(T_0 + T_1) =$

$(X_B(T_0+T_1), Y_B(T_0+T_1), Z_B(T_0+T_1))$. The coarse delay T_2')between the satellite and the ground station at the time can be determined by

$$T_2' = \frac{\sqrt{(X_B(T_0+T_1)-X_A)^2 + (Y_B(T_0+T_1)-Y_A)^2 + (Z_B(T_0+T_1)-Z_A)^2}}{c} \tag{6}$$

Linear extrapolation of the orbit $B(T_0 + T_1 + T_2')$ is to get the position of the orbit after experiencing a coarse time delay. Due to the rotation of the Earth, it is necessary to correct the coordinates of the satellite in the inertial coordinate system to the coordinates in the Earth-Fixed coordinate system. The corrected orbit can be $B'(T_0 + T_1 + T_2') = (X_B'(T_0 + T_1 + T_2'), Y_B'(T_0 + T_1 + T_2'), Z_B'(T_0 + T_1 + T_2'))$.

The signal transmission precision delay T_2 can be calculated by the corrected orbit. T_2 can be expressed as:

$$T_2 = \frac{\sqrt{[X_B'(T_0+T_1+T_2')-X_A]^2 + [Y_B'(T_0+T_1+T_2')-Y_A]^2 + [Z_B'(T_0+T_1+T_2')-Z_A]^2}}{c} \tag{7}$$

Assuming that T_0, T_1, and T_3 are known, Eq. (1) gives T_x.

The Beam Agility Control Pulse Generation Module generates the received signal pulse at T_x. Since the clock stability of the time maintenance module does not meet the time control requirements, the clock error needs to be considered when controlling the pulse generation. Assuming T_a is the whole second part of T_x and $T_b = T_x – T_a$ is the non-whole second part of T_x, the whole second starting point of T_x is determined by the on-board time and PPS. After the whole second starting point, the time when the hopping beam pulse is generated is the time when the local clock count is N. N can be expressed as

$$N = \left\lfloor T_b * (10^8 - E) \right\rfloor \tag{8}$$

where $\lfloor . \rfloor$ denotes the operation of rounding down.

In this paper, the position of the ground station is unchanged, and only the change of the satellite position is considered. The method of delay compensation for downlink and uplink is largely the same. For downlink communication, when calculating the delay compensation, to ensure that the onboard transmitting beam is received by the ground station at the time T_0, the extrapolated orbit needs to be modified to $B(T_0 - T_1 - T_2')$. And when correcting the orbit change due to rotation in the transmission process, α needs to be modified to $-\alpha$. The beam hopping time T_x can be written as $T_x = T_0 – T_1 – T_2 – T_3$.

4 System Performance Analysis

4.1 Visibility Analysis

The premise of communication between the satellite and the ground is that the ground station is within the coverage of the satellite. It can be assumed that the satellite's trajectory is a circular arc within the visible time range of the satellite to the ground station. It can be assumed that the radius of the Earth is *r and* the ground antenna pitch angle is θ. Setting the center of the Earth coordinate is $O = (X_o, Y_o, Z_o)$. There are the following relations.

$$|OB|^2 = |AB|^2 + r^2 + 2 * |AB| * r * \sin\theta \tag{9}$$

Equation (9) has two solutions that satisfy the conditions for the position of the satellite at the time of entry and the position of the satellite at the time of exit, which in turn allows the calculation of the visible period.

4.2 Analysis of Time Delay Error Estimation

In this paper, a section of the satellite orbital position visible to the station for 9.910 min is selected for simulation. We mainly analyze the satellite-ground transmission delay due to the rotation of the Earth and use the theoretical value to compare with the result value of orbit information simulation.

As shown in Fig. 2, the maximum satellite-ground transmission delay is 8.38 ms during the period when the satellite is visible to the Earth. The maximum speed of the satellite is 7.3 km/s. Substituting the two into Eq. (4), we can get that the maximum position theoretical error is 61.17 m. The corresponding time delay theoretical error is 203.913 ns which is a non-negligible error. Therefore, it is necessary to correct the orbit once according to the coarse estimated time delay. Correcting the coordinates of the satellite in the inertial coordinate system to the coordinates in the Earth-Fixed coordinate system., and then we calculate the satellite-ground transmission delay for the first iteration based on the corrected orbital position. The maximum transmission is 8.38ms, which generates a maximum error of 203.913 ns in transmission delay. If we iterate the orbit one more time, the transmission delay of the first iteration of the orbit is used to recalculate the coordinates in the Earth-Fixed coordinate system, which is equivalent to an accurate transmission delay of 203.913 ns. The error in transmission delay is 203.913 ns, and the maximum theoretical error of the position is 0.001489 m, which corresponds to the time delay theoretical error is 0.04962 ns. So the error is negligible. Therefore, another iteration of track position is needed to satisfy the calculation accuracy.

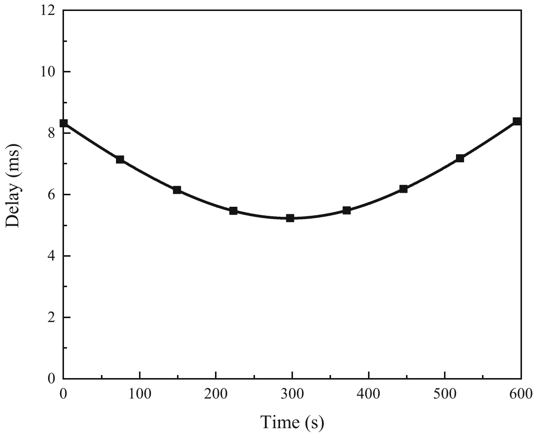

Fig. 2. Satellite to ground transmission delay.

The following analysis compares the transmission delay calculated by iterating the orbit position once with the coarse estimated delay with the coarse delay. As shown in Fig. 3, the red line shows the difference in simulation delay between the delay of the first iteration of the track position and the coarse delay, while the black line shows the difference in theoretical delay. It can be found that the maximum simulation error between the delay calculated by iterating the orbit position once and the coarse delay is 148.06 ns. Which has a gap compared with the theoretical value of 203.913 ns.

As shown in Fig. 4, the red line shows the difference in simulation delay between the first and second iterations of the track position, while the black line shows the difference in theoretical delay. It can be seen that the maximum delay error of the simulation result is 0.0026 ns which has a gap compared with the theoretical value of 0.4926 ns.

It can be seen that there are some deviations between the theoretical values and simulated results. This is due to the fact that the orbit position used in the calculation of the coarse delay is the orbit position at the moment of T0. In addition, due to the limitation of computational resources, the orbit value is calculated by linear interpolation rather than introduced by orbit dynamics.

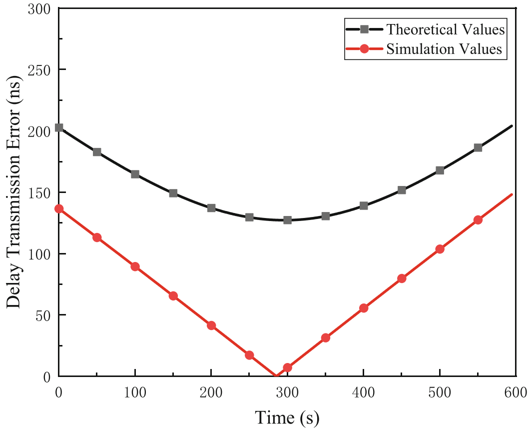

Fig. 3. Difference in time delay between iterating the orbit once and not iterating the orbit.

In summary, the delay compensation method proposed in this paper effectively improves the accuracy of the satellite-ground delay by correcting the orbital position through a two-iteration process compared with the direct calculation. It realizes that the signals transmitted from the ground station can still be accurately received by the sub-millisecond hopping receiving beam on the satellite even if they undergo millisecond transmission. This method helps save the expenses of communication resources.

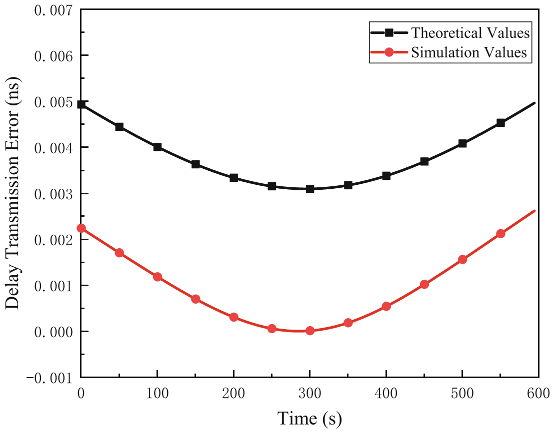

Fig. 4. Difference in time delay between iterating the orbit once and iterating the orbit twice.

5 Conclusion

This paper proposes a satellite communication beam agility control method for time synchronization using a highly stable clock and a global navigation system. The method first utilizes orbital information to calculate the coarse time delay between the satellite and the ground. Then, the orbital interpolation module is used to determine the orbital position of the received signal and corrections are made for the changes in the position of orbit in WGS-84 due to the rotation of the Earth during the transmission time. This allows for the calculation of the precise transmission delay of the signal. To ensure the signal is accurately received by the satellite's beam hopping within sub-millisecond precision, the orbital position needs to be iterated twice to enhance compensation accuracy. Simulation results show that this method improves the time delay accuracy by 148.06 ns compared to the traditional method. After two iterations of orbital position, the transmission delay error can be reduced to 0.0026 ns, meeting the required calculation precision.

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References

1. Li, K.L., Li, Y.T., Qiu, Z.K., et al.: Handover procedure design and performance optimization strategy in LEO-HAP system. In: 2019 11th International Conference on Wireless Communications and Signal Processing (WCSP), pp. 1–7. IEEE, Xi'an (2019)
2. Miao, J.S., Wang, P.J., Yin, H.Q. et al.: A multi-attribute decision handover scheme for LEO mobile satellite networks. In: 2019 IEEE 5th International Conference on Computer and Communications (ICCC), pp. 938–942. IEEE, Chengdu (2019)
3. Wang, L., Zhang, N.T.: Dynamic location management in LEO networks. In: The 13th IEEE International Symposium on Personal. Indoor and Mobile Radio Communications, pp. 1397–1401. IEEE, Lisbon (2002)

4. Musumpuka, R., Walingo, T.M., Smith, J.M.: Performance analysis of correlated handover service in LEO mobile satellite systems. IEEE Commun. Lett. **20**(11), 2213–2216 (2016)
5. Sun, S.H., Hou, L.M., Miao, D.S.: Beam switching solutions for beam-hopping based LEO system. In: 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), pp. 1–5. IEEE, Norman (2021)
6. Wang, Y.X., Bian, D.M., Hu, J., et al.: A flexible resource allocation algorithm in full bandwidth beam hopping satellite systems. In: 2019 IEEE 3rd Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), pp. 920–927. IEEE Chongqing (2019)
7. Liu, W.Y., Xia, S.Y., Jiang, Q.J., et al.: Hop-beam based resource scheduling algorithm for low orbit satellite networks. J. Chin. Acad. Sci. Univ. **37**(6), 9 (2020)