Precise Two Way Time Synchronization for Distributed Satellite System

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Abstract: The satellite to satellite precise ranging and time synchronization are necessary to distributed satellite system (DSS) and autonomous formation flyer (AFF) application. In satellite formation flying, the range between a cluster of co-orbiting or constellation satellites is very close, they collaborate with each other and perform special scientific missions cooperatively, so they can be regarded as a large single conventional satellite or virtual satellite. To accomplish the special scientific missions, a much higher accuracy requirement is put forward for time synchronization and ranging measurement in the DSS and AFF. Firstly, a detailed description of the principle and key techniques of dual one-way ranging and time synchronization are presented. For further study, the simulation and performance evaluation of the equipment are discussed. Secondly, to adapt the condition of high dynamic in two-way observation module, the digital base-band processing algorithms of spread spectrum pseudo-code is investigated. Meanwhile, the signal generation and fast acquisition of spread spectrum signal are implemented. The methods of designing for code tracking loop, cycle slip detection, ambiguity resolution and carrier loop are also investigated. The results of simulation indicate that the accuracy of the terminal device is less than 0.2m and 0.5ns (1σ) in precise ranging and time synchronization. The time synchronization error is less than ±10ns for a range less than 200km in formation flying.

Keywords: Time synchronization, Distributed satellite system, Autonomous formation flyer, Two way time synchronization.

Ⅰ Introduction.

Two-way time synchronization and transfer is one of the most accurate ways to compare clocks in different systems or remote stations. The high accuracy is obtained by the users simultaneously exchanging signals via a communication satellite in conventional time transfer. For the paths between the clocks are reciprocal or very nearly, so the common delays cancel. The difference between the clocks is then half the difference in time interval counter readings. The main advantage of the two-way technique is that no knowledge is required concerning the location of the clocks or satellite with a minor exception of the Sagnac effect, which is easily calculated. The major disadvantage of the system is the participants must be able to simultaneously transmit and receive signals. Two way has a history about 50 years for synchronization of clocks. Experiments have been conducted using numerous different satellites, signal structures, modulation techniques, and carrier frequencies[1]. Now, TWSTFT is one of the primary methods for international remote time transfer and time dissemination, and obtain a very high accuracy of several sub-nanoseconds to several nanoseconds. In recent years, this method has been expanded to many applied science and technology,[3-6] and this method is a new way to perform the space-based missions for precise ranging and time synchronization. Satellite formations in low earth orbit encounter perturbing gravitational forces due to deviations from spherical in the Earth's shape. MIT Space Systems Laboratory researchers are working on ways to linearize the models of these effects to allow more precise control of relative satellite positions in orbit.[6] Distributed satellite system (DSS) is a cluster of small satellites that cooperate to perform the function of a large, single conventional satellite. The relative measurement and control is its key technology. In the relative observation and the relative status and attitude determination, four major approaches are widely utilized.

- Relative measurement based on radio;
- Relative measurement based on differential GPS;
- Relative measurement based on optical;
- Relative measurement based on dynamics model.

For time synchronization in DSS, there are two major approaches, one is precise GPS time synchronization in low earth orbit (LEO) satellite using code and carrier phase observation, the other is precise dual one way time synchronization.

Ⅱ Principle of dual one-way precise ranging and time synchronization.

The basic principle of two-way time and frequency transfer (TWTFT) using a geostationary (GEO) communication satellite is illustrates in figure 1. TWTFT is one of the most accurate ways to compare clocks in remote time scales on the earth station in time keeping. More than 15 comparison links has established for computation the international atomic time (TAI) in BIPM.

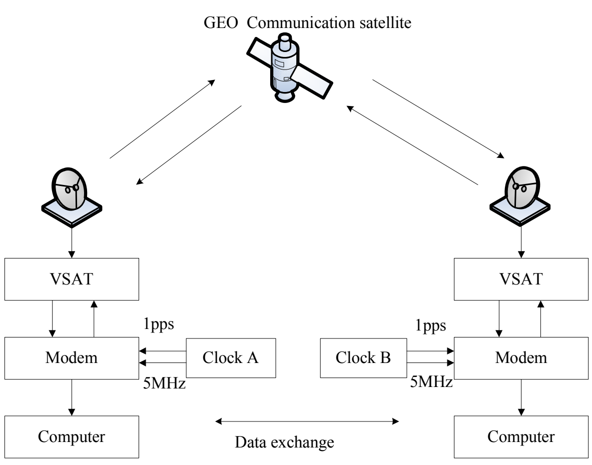

Fig.1 Basic principle of TWTFT using a GEO communication satellite in time laboratory.

Likewise, dual one-way time synchronization and raging are potentially one of the most accurate ways to achieve a high precision clock difference and precise ranging in AFF and DSS. The basic principle and widely application are investigated in recent years, some observation satellite system has prepare to use this approach in AFF. This section introduces the simple principle of dual one-way time synchronization and ranging (DOWT&DOWR) with emphasis on its use with distributed satellite system.

The principle of DOWT & DOWR is shown in figure 2. The approach is based on two kinds of measurement, code division multiple access (CDMA) utilization spread spectrum and carrier phase observation like global navigation system (GPS), its corresponding issue is two kind of pseudo-range observations between the spacecraft from the code and carrier phase observation. As shown in figure 2, we can be written the time difference measurement as [2],

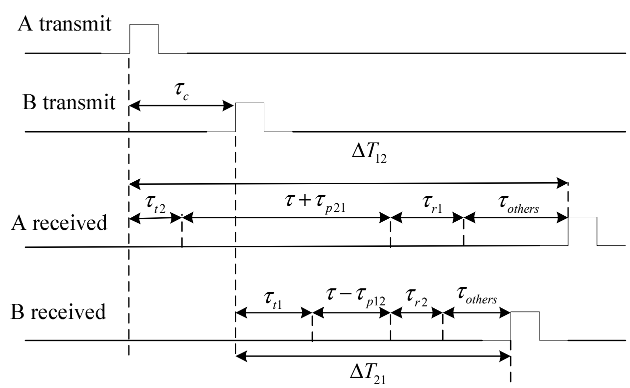

Fig.2 Principle of DOWT & DOWR.

$$\Delta T_{12} = \tau_{t2} + \tau_{p21} + \tau_{r1} + \tau_c + \tau_{ion21} + \tau_{trop21} + \tau_{s21} \quad (1)$$

$$\Delta T_{21} = \tau_{t1} + \tau_{p12} + \tau_{r2} + \tau_c + \tau_{ion12} + \tau_{trop12} + \tau_{s12} \quad (2)$$

where $\Delta T_{12}, \Delta T_{21}$ are the time difference in transmitting and receiving signal pulse between the satellite A and satellite B, which can be measured by the space borne receiver, τ_{t1}, τ_{r1} and τ_{t2}, τ_{r2} are the equipment delay and receiver noise caused by radio transmitter and receiver from the spanned space borne device respectively, τ_c is the clock difference between satellite A and B, τ_{p21}, τ_{p12} is the radio propagation delay between the phase center of two antennas, τ_{s21}, τ_{s12} is the earth rotation effect time delay, which is called Sagnac effect, it can be derived using theoretical calculation, $\tau_{s21} = A\omega / c^2$, where, c is the velocity of light, ω is the earth's rotation rate, and A is a parameter defined by the relative position between each satellite to the earth center, τ_{ion21}, τ_{ion12} and $\tau_{trop21}, \tau_{trop12}$ are the delay caused by ionosphere and troposphere impact. We can find the major difference in equation (1) and (2) is, we, here introduced into the earth rotation effect, Sagnac effect and ionosphere delay and troposphere delay in observation, this mainly because of the two terms are the major error in a relative long distance AFF. And it has large difference from TWSTFT in remote time transfer.From the equation (1) and (2), we can obtain the τ_c,

$$\tau_c = \frac{1}{2}[(\Delta T_{12} - \Delta T_{12}) - (\tau_{t2} - \tau_{t1}) - (\tau_{r1} - \tau_{r2}) \\ - (\tau_{p21} - \tau_{p12}) - (\tau_{ion21} - \tau_{ion12}) \\ - (\tau_{trop21} - \tau_{trop12}) - (\tau_{s21} - \tau_{s12})] \quad (3)$$

If the signal propagation paths are reciprocal, i.e. $\tau_{p21} = \tau_{p12}$, likewise, the pseudo-range P can be written as

$$P = \frac{1}{2}[(\Delta T_{12} + \Delta T_{12}) - (\tau_{t2} + \tau_{t2}) - (\tau_{r1} + \tau_{r2}) \\ - (\tau_{ion21} + \tau_{ion12}) - (\tau_{trop21} + \tau_{trop12}) \\ - (\tau_{s21} + \tau_{s12})]c \quad (4)$$

where c is the velocity of light in the vacuum.

In case of $\tau_{ion21} = \tau_{ion12}, \tau_{trop21} = \tau_{trop12}$, the equation (3) and (4) can be simplified. And in AFF&DSS, $\tau_{trop21} = \tau_{trop12} = 0$, so the above two equation can be rewritten as

$$\tau_c = \frac{1}{2}[(\Delta T_{12} - \Delta T_{12}) - (\tau_{t2} - \tau_{t1}) - (\tau_{r1} - \tau_{r2}) \\ - (\tau_{ion21} - \tau_{ion12}) - (\tau_{s21} - \tau_{s12})] \quad (5)$$

$$P = \frac{1}{2}[(\Delta T_{12} + \Delta T_{12}) - (\tau_{t2} + \tau_{t2}) - (\tau_{r1} + \tau_{r2}) \\ - (\tau_{ion21} + \tau_{ion12}) - (\tau_{s21} + \tau_{s12})]c \quad (6)$$

The equation which utilized in carrier phase observation we can also developed in the same way. In this more precise method, just as GPS carrier phase measurement like, the cycle slip detection and construction and the ambiguity resolution fix is more difficult than GPS, for the system possess a ordinary stability of frequency standard. Therefore, the cycle slip is taken place frequently in the observation.

From equation (5) and (6) the relative range and clock difference has been achieved, and the precision of the two observation quantity are the same level, which is mainly depend on the performance of the space borne atomic clock and the equipment level. The relationship between the relative frequency stability and the interval of observation is given as formula (7).

$$\tau_e = \frac{\Delta f}{f} T_i \quad (7)$$

where τ_e is the error of time synchronization between any of the spacecraft, $\Delta f / f$ is the frequency stability, T_i is observation time interval which can select according to the performance of the atomic clock.

Ⅲ Simulation of DOWR and DOWT.

To implement the simulation, we assume that carrier frequency is 400MHz, i.e. wavelength of 75 centimeters, and a pseudo random noise (PRN) chip rate of 1.023 MHz (that is, a chip width of 293 meters). As we know, the GPS carrier phase position and time transfer has acquired a very high precision, the same result, however, was not achieved because the carrier phase ambiguity resolution algorithm is low efficient. A software receiver approach is discussed in this section. The general construction is shown in Figure 3. The signals transmitted from the satellites are received from the antenna. Through the radio frequency (RF) chain the input signal is amplified to a proper amplitude and the frequency is converted to a desired output frequency. An analog-to-digital converter (ADC) is used to digitize the output signal. The antenna, RF chain, and ADC are the hardware used in the receiver. After the signal is digitized, software is used to process the IF signal. Acquisition means to find the signal of a certain satellite. The tracking program is used to find the phase transition. The acquisition and tracking method are investigated. Figure4 illustrates the structure of code and carrier tracking loop.

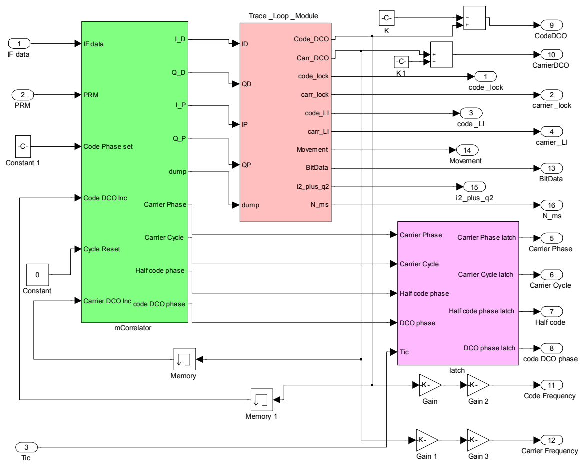

Figure 3 General configuration of the simulation.

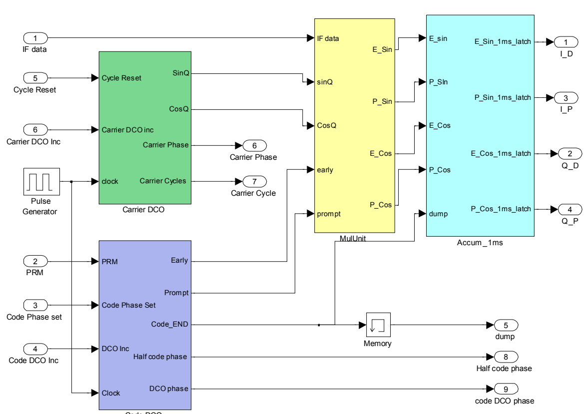

Figure4 Code and carrier tracking loop.

Ⅳ Simulation analysis.

For analysis the error of precise ranging and time synchronization in above mentioned. We simulated a simple situation which here, called follow formation model based on Simulink and STK(satellite tool kit), in this model, satellite A, B, C and D are into the same orbit(co-obiter), for easy study, we called satellite A is reference satellite, the other three are so called follow formation flying satellite, the distance between any of satellite is 50km, and we assume that the semi-major axis is 340km. Figure 5 is the sketch map of the follow formation flying in the simulation.

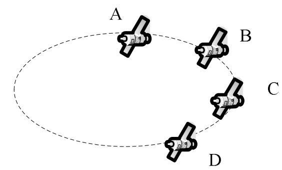

Figure.5 Sketch map of follow formation flying.

Figure 6 illustrates the error sequence of time synchronization between satellite A and B, A and C, A and D utilization code observation. Figure 7 illustrates the error sequence of time synchronization between satellite A and B, A and C, A and D utilization carrier phase observation. From figure 6 and 7 we can see that the two methods have almost the same precision level.

As figure 6 and 7 shown, the RMS of the sequence is given in table 1. From table 1 we can see that carrier phase observation is better than the code, we introduce some cycle slips artificially and using the double difference cycle slip detection methods. For the carrier frequency is 400MHz, the small cycle slip is much easier for detection, correspondingly, because a bad frequency stability is adopted in simulation study, so the cycle slip is take place more frequently than GPS.The ambiguity resolution is also a major issue just like GPS carrier phase observation. Additionally, from table 1, we can

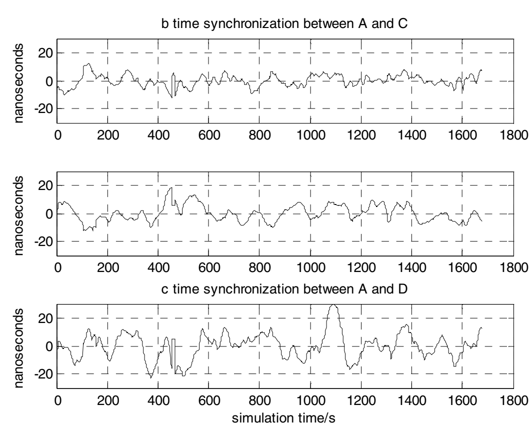

Figure 7 Error sequence of time synchronization using spread spectrum code observation.

find that the error of time synchronization between the satellites is less than ±10ns, and the RMS become worse with the variety of distance between the satellites.

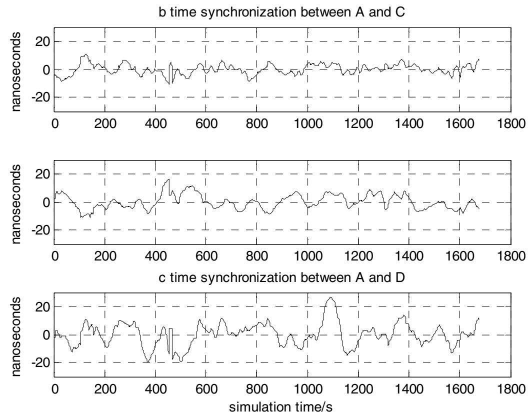

Figure 8, The error sequence of time synchronization using carrier phase observation.

Table 1 RMS of the two methods.

Type	A and B(ns)	A and C(ns)	A and D(ns)
Code	4.2	5.9	9.5
Carrier	3.7	5.1	8.3

Eventually, the results of simulation indicate that the accuracy of the terminal device is less than 0.2m and 0.5ns (1σ) in precise ranging and time synchronization. It is suitable for the DSS precise ranging and time synchronization.

Ⅴ Conclusion.

In this paper, a detailed description of the principle and key techniques of two-way ranging and time synchronization are presented. The simulation and performance evaluation of the equipment are discussed. To adapt the condition of high dynamic in two-way observation module, the digital base-band processing algorithms of spread spectrum pseudo-code is investigated. The signal generation and fast acquisition of spread spectrum are implemented. The methods of designing for code loop and carrier loop are also described. The results of simulation indicate that the accuracy of the terminal device is less than 0.2m and 0.5ns (1σ) in precise ranging and time synchronization in satellite formation flying. The error time synchronization is less than ±10ns for a range between the satellites less than 200km.

Acknowledgement The authors would like to thank Dr. ZHONG XingWang for his helpful discussions.

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