

Design and experiment of onboard laser time transfer in Chinese Beidou navigation satellites

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Abstract

High-precision time synchronization between satellites and ground stations plays the vital role in satellite navigation system. Laser time transfer (LTT) technology is widely recognized as the highest accuracy way to achieve time synchronization derived from satellite laser ranging (SLR) technology. Onboard LTT payload has been designed and developed by Shanghai Astronomical Observatory, and successfully applied to Chinese Beidou navigation satellites. By using the SLR system, with strictly controlling laser firing time and developing LTT data processing system on ground, the high precise onboard laser time transfer experiment has been first performed for satellite navigation system in the world. The clock difference and relative frequency difference between the ground hydrogen maser and space rubidium clocks have been obtained, with the precision of approximately 300 ps and relative frequency stability of $10E-14$. This article describes the development of onboard LTT payload, introduces the principle, system composition, applications and LTT measuring results for Chinese satellite navigation system.

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Keywords: Navigation satellites; Time synchronization; Laser time transfer (LTT); Measuring experiment; Satellite laser ranging (SLR)

1. Introduction

The global navigation satellite system (GNSS) has been widely used in navigation, positioning, timing and navigation-related sciences (Jin et al., 2006, 2009, 2010, 2011). High precision time synchronization between satellite and ground station plays the key role in satellite navigation systems. Time synchronization precision would affect the satellite ranging error, the broadcast ephemeris error and influent user's navigation accuracy, which is a key technology to improve the navigation accuracy. The ionosphere and troposphere affect the microwave propagation differently at different time making system error uncertain,

although the microwave technique is generally adopted for the time transfer between a satellite and a ground station. For laser wavelength, the effect is much less, the transfer delay much smaller, and the system error much more stable. The advantages of laser measurement technique have been proved by the application of satellite laser range (SLR) technology (Exertier et al., 2006). So laser time transfer (LTT) derived from SLR technology could calibrate a pseudo-random-noise modulated microwave time transfer system, evaluate the short-term performance of satellite clock, and improve the prediction precision of satellite clock, which is especially important for navigation satellites.

The first experiment of laser time transfer (LTT) between a satellite and ground stations was LASSO (Laser Synchronization from Stationary Orbit). In 1989 and 1992, the experiment was carried on between European and

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American continents. The accuracy of time measurement for two atomic clocks located in OCA Observatory, France, and McDonald Observatory, US, respectively, is 100 ps, and the accuracy of relative frequency stability is $10E-13/1000$ s (Fridelance et al., 1995).

Shanghai Astronomical Observatory (SHAO) has researched on SLR technology and time measurement by laser ranging technique for many years (Yang et al., 2004a,b, 2006; Li and Yang, 2004). According to the principle of LTT, SHAO has designed and developed the prototype of LTT module in 2005. The ground test was carried out for the prototype, which was used to verify the feasibility of laser time transfer method by the way of the simulating satellite and ground clocks (Wang et al., 2008). Based on LTT prototype and improvements considered, SHAO have developed multi sets of onboard LTT payloads and all ones passed through space environment condition tests. Those onboard LTT payloads were successfully applied to Chinese navigation satellite with Medium Earth Orbit (MEO) and Inclined Geostationary Orbit (IGSO) at the orbital altitude of 21,500 km and 36,000 km.

By using the SLR system, with strictly controlling laser firing time and developing the LTT data processing system on ground, the high precision LTT experiments on MEO navigation satellite have been carried out for the first time in the world in Jan. 2008. In Aug. 2010 and May 2011, LTT measurements for IGSO navigation satellites have been also performed. The clock difference and relative frequency difference between the ground hydrogen maser and China-made space rubidium clocks have been obtained, with the precision of 300 ps and relative frequency stability of $10E-14$, which met designed performances. The spaceborne single photon laser detector was also for the first time used in satellite navigation system in the world, which opens some new opportunities on the field of the high precise space photon detection technology.

After Chinese first successful LTT experiment in Jan. 2008, T2L2 (Time Transfer by Laser Link), developed by both CNES and OCA was in its operation onboard the satellite Jason 2 since June 2008, which orbit is about 1300 km. The time accuracy is about 100 ps (Samain et al., 2011).

Chinese LTT experiment also encouraged other laser time transfer project. The European Laser Timing (ELT) Experiment with the support of the frame of the ESA mission “Atomic Clock Ensemble in Space” is now in process, which is the further develop version of Chinese LTT project. The ELT payload will be launched in 2015 with the orbit of hundreds kilometers (Schreiber et al., 2010).

Until now, Chinese LTT experiment is the only laser time synchronization project onboard navigation satellites.

2. The principle and system configuration of LTT

2.1. Principle

The principle of LTT between a satellite and a ground station is shown in Fig. 1. Laser pulses are emitted from

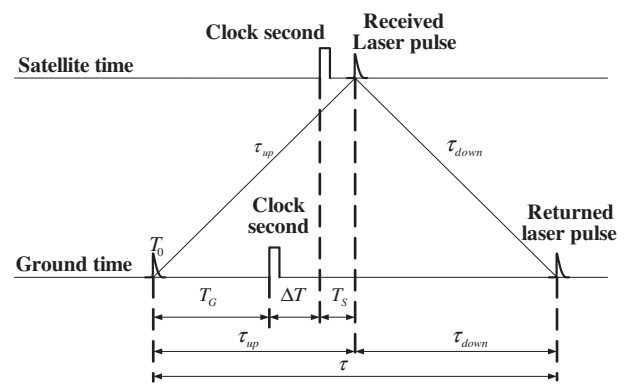


Fig. 1. Principle of laser time transfer (LTT).

the ground station to the satellite, and then reflected back to the ground station by the onboard retro-reflector. The time interval (T_G) between the transmitted laser pulse and the following second pulse of ground clock is measured by the ground station, while the time interval (T_S) of the laser pulse received at the satellite and the former second pulse of satellite clock is measured by onboard equipment. The uplink of laser pulses flight time (τ_{up}) can be got from the round-trip of laser flight time (τ) measured at the ground station.

So, we have

$$\Delta T = \tau_{up} - T_S - T_G + \epsilon \quad (1)$$

where ϵ is the total system error, and ΔT is the time difference between the onboard and ground clocks.

2.2. System configuration and performance

The LTT measuring system mainly includes onboard instruments, ground satellite laser ranging station and data processing system. The diagram of the LTT measuring system is shown in Fig. 2.

There are two main instruments onboard, laser retro-reflect array (LRA) and LTT payload. The LRA (designed by SHAO) reflects the laser back to the ground for laser ranging. The LTT payload detects the laser pulses, measures the time interval between laser arriving at satellite and the former 1 pps pulse produced by onboard atomic clock (T_S), and then sends T_S to ground.

In the ground SLR station, a SLR telescope and a laser are basic. There are two event timers, one records the laser round-trip flight time in order to obtain laser uplink flight time τ_{up} , and the other records the laser firing time and ground 1 pps pulse in order to get T_G . A microwave receiving equipment is needed to get T_S from LTT onboard. The clock difference then can be calculated according to the formula (1).

In our LTT system, the laser frequency is 20 Hz, so the LTT payload is designed as 20 Hz. Twenty T_G and T_S value will be produced per second. Because of the limited capability of the navigation channel, the T_S data will be primarily processed, selected one value in twenty per second, and then transmitted to the ground. Another teleme-

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