Recent Advances in Pulsed Laser Time Transfer on China Space Station

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Abstract

The Laboratory Module II of the China space station (CSS), namely the Mengtian lab experiment module, was launched in October 2022. A Sr optical clock, H-maser, and laser-cooled microwave clock were placed on the CSS, with a microwave link, and a pulsed laser link. And the laser time transfer on the CSS (CLT) mission is led by the Shanghai Astronomical Observatory (SHAO). In this paper, recent advances of main instruments in the CLT mission were described in detail, including the parameters and performance testing of the photodetector and its optics, the on-board event timer, the laser retro-reflector array, and the ground stations. Here we report ground-based laboratory tests of the CLT payload, with a precision of 22～27ps and instability of less than 0.8ps over 86400s and 0.09ps over 300s. Currently, the CLT spaceborne equipment has been launched and the CLT ground stations are under construction. After months of preparation in orbit, there will be opportunities to carry out space-to-ground and ground-to-ground pulsed laser time transfer experiments. Welcome your stations to participate.

1. Introduction

In recent years, several international space projects with atomic clocks have been developing, such as European Laser Timing (ELT) on ISS[1] and Laser Time Transfer (LTT) on Beidou[2]. The Laboratory Module II of the CSS project is equipped with a Sr optical atomic clock, H-maser, and laser-cooled microwave clock, which have been launched successfully. And a microwave and pulsed laser time-frequency comparison links were placed to contribute to the understanding of the onboard clock behavior, tests of general relativity, and the realization of atomic time scales, etc. The pulsed laser time transfer technique is a promising technique, with highly accurate and fewer time delays. According to the CSS mission, the performance of CLT is expected to reach a time stability of 0.1ps over 300 s, and 1ps over 86400s.

This paper aims to report recent advances in CLT, including the onboard payload and ground stations. We describe in detail the mission design and core components of the CLT payload, detection optics, event timer, and laser retro-reflector array, as well as the payload testing results of the ground laboratory. At present, the CLT spaceborne equipment has been developed and launched, and two dedicated ground stations are also being built. A period of several months is needed to carry out the atomic clock debugging and other preparations. Then, we will use CLT based on ground stations to understand the performance of onboard clocks, as well as carry out ground-to-ground time-frequency dissemination experiments.

2. The CLT payload mission

The CLT mission concept of operations is shown in Figure 1. The CLT system consists of a CLT payload, ground SLR stations, a data processing system, as well as a radio data transmission link. In case of the CLT payload, the key components are two same event time devices with THS788 chips, two same detection optics operating in a single photon mode, and a laser retro-reflector array consisting of four corner cube retro-reflectors, whose characteristics will be described in detail later. The on-board optical atomic clock will provide the CLT payload 200MHz clock optical signals that must be converted into 200MHz electrical signals by a photoelectric conversion instrument of CLT and used as a frequency reference for the on-board event timer.

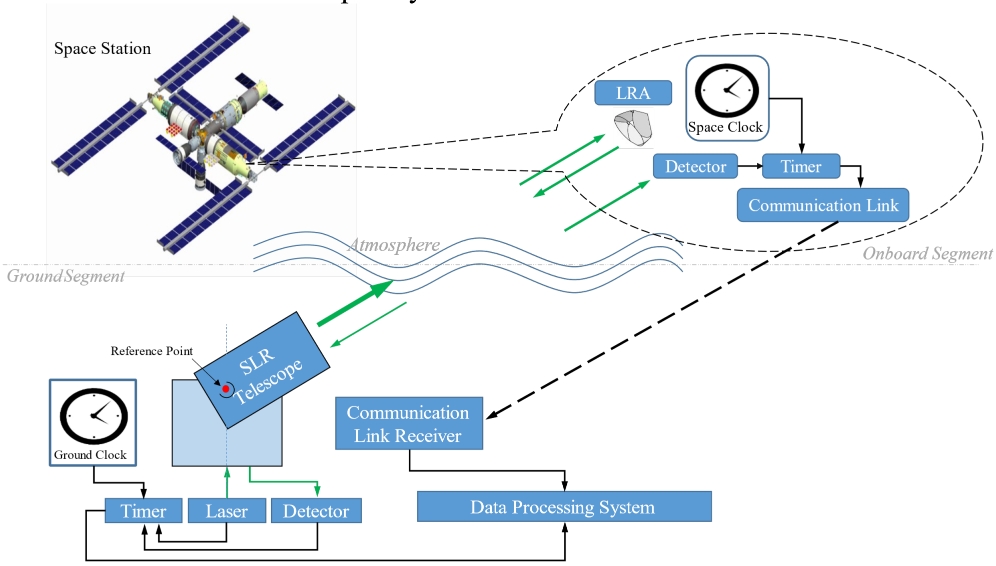


Figure 1. The CLT mission concept of operations

The design CLT is shown in Figure 2. The size of the CLT unit is 230×190×169 mm, the mass amounts to 6.5 kg, and its power consumption approximately to 24W with fluctuations up and down because of different working modes. In case of the CLT payload, event timer, single photon detector, and detector optics all provide redundancy design to ensure the CLT mission reliability. The LRA and detector optics are installed on an identical structure to keep their position relationship stable. For the LRA design, there is a small pyramid with 4 CCRs, each of which has a clear aperture of 33mm. And the CLT payload has 3 circuit boards inside, a detector and timer circuit, an interface circuit and a power circuit. In addition, the detection unit of CLT payload has a big field of view of more than 120 degrees. or 14~60 degrees incidence, corresponding to 20~85 degrees of tracking elevation, due to lower orbit altitude (400 km) and shorter passing time (200 s) of CSS.

The CLT payload will operate in green light with laser pulse repetition of 1kHz, 2kHz, and 10kHz. According to the CLT mission, the CLT link is expected to reach a fractional frequency uncertainty level of less than 1ps over 86400s and 0.1ps over 300s. The key to achieving this goal is to ensure single photon detection and constant temperature for both onboard CLT payload and ground SLR systems. In case of CLT unit temperature control, a liquid cooling method is used.

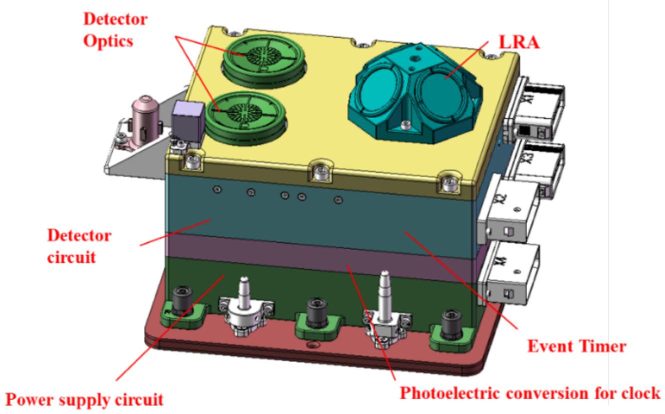


Figure 2. The CLT payload design

3. Characterization of the CLT flight instrument

3.1 Detector and its optics

The photon detector is a key part of pulsed laser time-frequency transfer, which can convert laser pulse optical signals into electrical signals with a high precision. The CLT detector is based on an avalanche photodiode operating in Geiger mode, and its chip is K14 SPAD of 100 micrometers with 25ps precision by the Czech Technical University of Prague.

The single photon avalanche diode detector is widely used in the field of SLR. As we all know, its measurement precision and stability are related to echo energy. In order to study the relationship between counting rate and K14 SPAD performance and achieve a better stability, some special testing experiments are carried out. We find the laws of delay and precision changed with counting rate through measurements. The recommended counting rate is 5~20%, approaching single photon level (see figure 3).

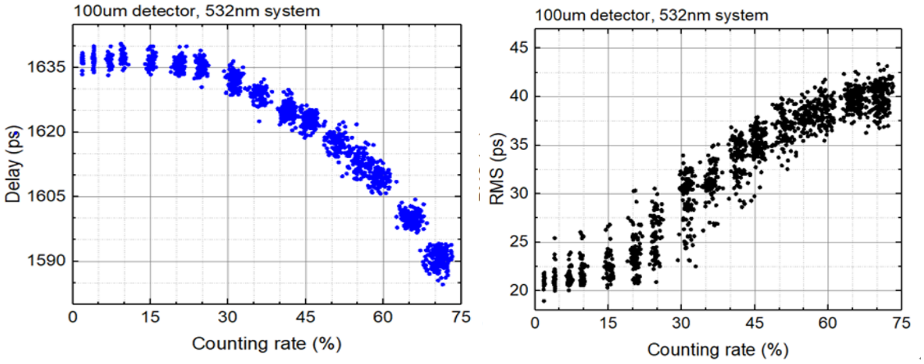


Figure 3. For the K14 SPAD chip, laws of delay and precision changed with counting rate

In addition, the CLT photodetector used time-delay temperature compensation technology to reduce the dependence on temperature control, and improve the CLT payload measurement stability. The photodetector used an avalanche voltage compensated circuit and fine adjustment of the resistance circuit to lower the temperature drift. We finally managed to set it to a level of 0.1ps / Kelvin. To reduce the negative impact of strong background noises on the CLT photodetector, we choose an operating mode of gate control which means the detector is effective only in the gate and the ground SLR stations have to achieve precise control on laser emission epoch.

We design detection optics, partly borrowing from the ACES ELT mission[1], to meet the requirements of the CLT mission, such as a large field of view, background noise, and single photon detection. The CLT detection optics design is shown in figure 4, with a snowflake attenuator, a Polytetrafluorethylene (PTFE) scatter, pinholes, and a filter. The snowflake plate gives a selective attenuation dependent on incidence, contributing to maintaining a stable counting rate for the CLT photodetector. The PTFE scatter have less relative transmittance change at different laser incidence angles than ground glass selected by the ELT mission. The FWHM of the narrow bandpass filter is 4 nm, used for spectrum filtering. Internal pinholes can reduce light noise from multiple internal reflections.

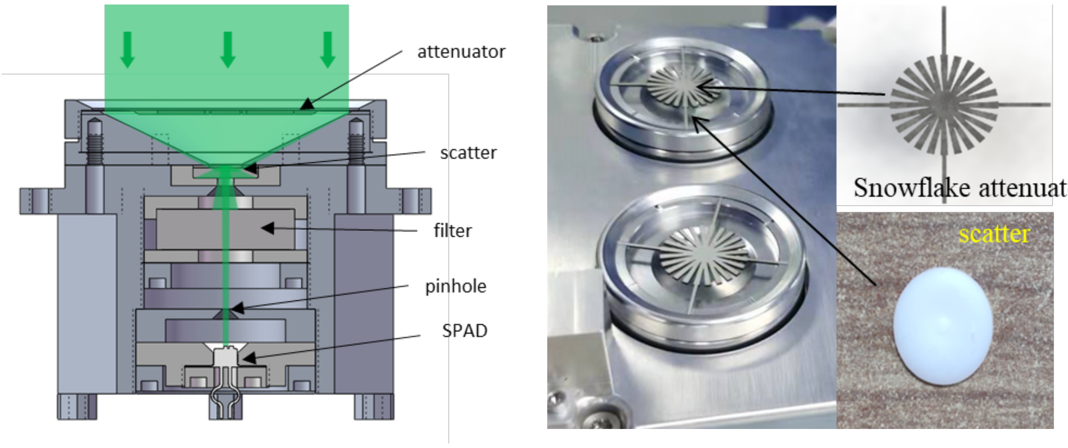


Figure 4. The CLT detection optics design

Based on the parameters of PTFE scatter and snowflake attenuator, as well as the laser radar equation, we calculated that the relative variation of photons reaching the detector target plane is 25% (see figure 5). The relative change can be defined as the ratio of the minimum to the maximum.

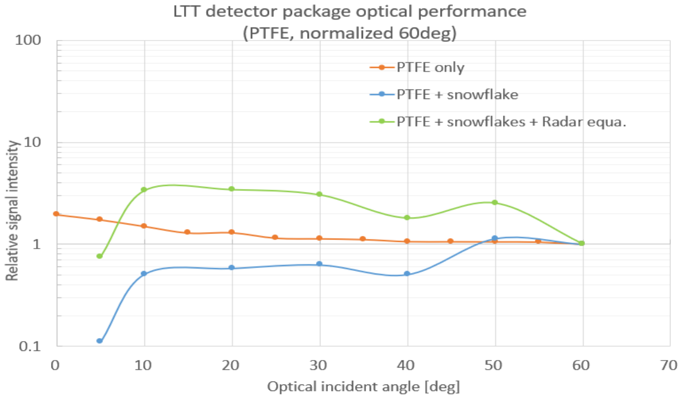


Figure 5. The CLT detector optical performance

3.2 Event timer

The event timer is another vital part of the CLT payload that get the time stamping of photodetector electrical signals in the CLT time scale. The 200MHz optical signal of the optical atomic clock is converted by a photoelectric conversion module to a 200MHz electrical signal which is used as the frequency benchmark for the CLT event timer. And a 1pps reference for the CLT event timer comes from the CSS orbiting receiver which is synchronized with UTC.

We use an FPGA and timing chip THS788 to develop a high-precision event timer. The measurement precision is about 8ps, the nonlinear error is less than 1ps, the measurement frequency is up to 20kHz, and time stability is better than 40 fs over 300s and

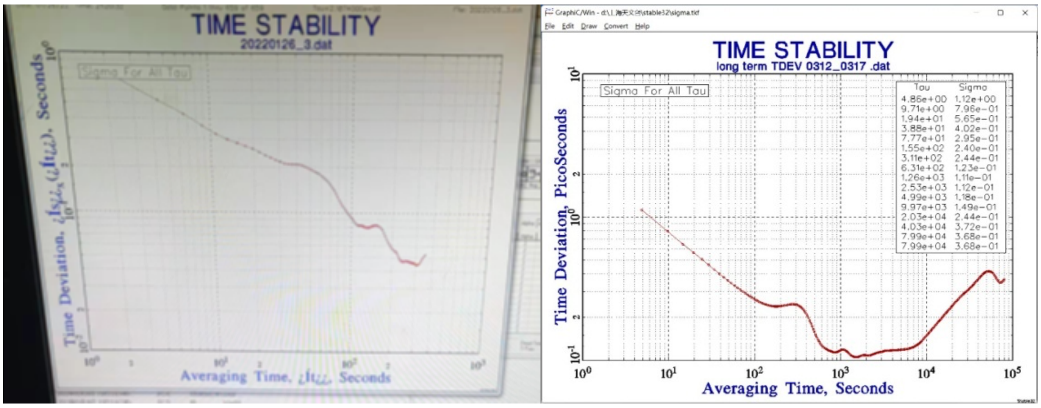
100fs over 86400s. Considering that a single channel measurement of the CLT event timer is affected by temperature fluctuations and aging, the reference frequency division signal is used as the calibration signal to realize the real-time calibration of the delay drift, similar to that of the T2L2 mission[3].

3.3 Laser retro-reflector array

The laser retro-reflector array is pyramid-shaped, similar to that of the CHAMP satellite, which consists of four corner cube retro-reflectors installed on a four-prism platform. Four corner cube retro-reflectors are uniformly distributed on the side surface of a four-prism platform, and the center of the incident plane of the retro-reflectors is on the same sphere. The angle is 45° between the normal line of a single retro-reflector and that of the retro-reflector array. The size of the retro-reflector unit is 92×92×45 mm, the mass amounts to 320 kg and the active reflecting area to more than 30% of the maximum within FOV of 120° degrees.

3.4 ground testing of the flight payload

The performance of the CLT package was verified in a series of ground lab tests, with a 10 kHz repetition rate and 10ps pulse width laser source. Figure 7 shows the ground-based laboratory tests of CLT with a precision of 22～27ps and an instability of less than 0.8ps over 86400s and 0.09ps over 300s.



Tau	Sigma
4.86e+00	1.12e+00
9.71e+00	7.96e−01
1.94e+01	5.65e−01
3.88e+01	4.02e−01
7.77e+01	2.95e−01
1.55e+02	2.40e−01
3.11e+02	2.44e−01
6.31e+02	1.23e−01
1.26e+03	1.11e−01
2.53e+03	1.12e−01
4.99e+03	1.18e−01
9.97e+03	1.49e−01
2.03e+04	2.44e−01
4.03e+04	3.72e−01
7.99e+04	3.68e−01
7.99e+04	3.68e−01

Figure 6. TDEV of the CLT payload measured in a ground lab. Left: Short term stability; Right: Long term stability

4. The CLT ground station mission

The CLT mission is based on the existing SLR system. Two dedicated CLT ground stations are under construction in China. A removable one is built in Xi'an, and another fixed one is in Beijing (see figure 8). For both stations, the receiving telescope is 40cm, the laser is 10kHz, 0.4mJ of laser energy, and the laser divergence is less than 10 arcsecond.

To the CLT mission, there are several higher requirements compared with the traditional SLR stations. First, it is necessary for the ground SLR stations to accurately control the laser fire epoch as the photodetector gate of CLT is fixed with its interval of 100us (10kHz). And the control accuracy is expected to be better than 10ns to reduce the influence of background noise. Second, ensuring a single photon detection mode for both the CLT payload and the ground station is significant, which is key to better time stability. Another, the ground stations have to identify and calibrate the one-way delays with high accuracy and precision and reach time stability better than 1ps over 86400s and 0.1ps over 300s.

Figure 7. Two dedicated ground stations are under construction in China. A removable one is built in Xi'an (Left), and another fixed one is in Beijing (Right).

5. Conclusions

The Laboratory Module II of the CSS has been launched at the end of October 2022. The Shanghai Astronomical Observatory (SHAO) is responsible for the CLT link, cooperated with Technology and Engineering Centre for Space Utilization, which is used to assess the stability of on-board atomic clocks and carry out tests of fundamental physics. The onboard hardware mainly consists of a laser retro-reflector, a single photon detector package, and an event timer. And the characteristics and performances of the CLT payload are described in detail. The photodetector chip is K14 SPAD with 25ps precision. The photodetector counting rate of 5～20% is good for the CLT mission. The detection optics can guarantee 25% relative change of photons for different optical incident angles. The FPGA and timing chip THS788 were selected to develop a high-precision event timer with a precision of 8ps and a maximum measurement frequency of 20kHz. And a real-time calibration channel of the delay drift was developed to reduce the negative impact of temperature fluctuations and aging. The performance of the CLT package was verified in ground lab tests, with a precision of 22～27ps and an instability of less than 0.8ps over 86400s and 0.09ps over 300s.

Compared with the traditional SLR stations, CLT ground stations has higher requirements, such as the laser fire epoch control, the laser power density adjustable, the identification and calibration of one-way delays, as well as the higher time stability with better than 0.1ps over 300s and 1ps over 86400s. Currently, two new SLR stations with an aperture of 40cm have been constructing for the CLT mission. At the beginning of 2023, the CLT link will provide the scientific data for assessing the onboard atomic clock, and welcome your stations to participate.

References

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