Performance of laser time-frequency transfer system in China Space Station

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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. The CSS mission's pulsed laser time-frequency transfer (CLT) system is led by the Shanghai Astronomical Observatory (SHAO). This paper aims to present the development and performance evaluation of the CLT system.

The CLT payload unit measures 230×190×169 mm, with a mass of 6 kg and power consumption of approximately 25 W, subject to fluctuations depending on the operating mode. The onboard hardware includes a laser retro-reflector, a single-photon detection package, and an event timer. The CLT detector utilizes an avalanche photodiode operating in Geiger mode, with the K14 SPAD chip featuring a 100-micrometer detection area and a timing precision of 20 ps. The detection optics system has snowflake attenuators, polytetrafluoroethylene (PTFE) scatterers, pinholes, and an optical filter. An FPGA and the THS788 timing chip were employed for high-precision event timing, achieving a timing accuracy of 8ps and supporting a maximum measurement frequency of 20 kHz. Several technical challenges were addressed to meet the stringent requirements of space-to-ground laser time-frequency transfer for the Chinese space station. These included enhancements in large-field optical intensity stability detection, compensation for temperature drift-induced delays in the detector, and high-repetition-rate measurements at 10 kHz to improve overall stability. Additionally, a real-time calibration channel for compensating delay drift was developed to mitigate the impact of temperature fluctuations and aging effects in the CLT event timer.

The temperature-induced delay drift of the CLT detector is mitigated through optimization of the comparator configuration and bias voltage, including adjustment of the feedback coefficient. Experimental results demonstrate that, with a turning point at 21°C, the CLT detector achieves temperature drift compensation of 0.14ps/°C when operating above 21°C. The detection optics maintain a 25% relative photon change across varying incident optical angles. Ground-based laboratory tests have confirmed that the CLT payload achieves a timing precision of 23ps, with instability of less than 0.5ps over one day and 0.09ps over 300 seconds.

Ranging experiments using the CLT laser retro-reflector array (LRA) were conducted by ground-based satellite laser ranging (SLR) systems located in Shanghai, Xi'an, and Beijing. Additionally, dedicated CLT ground stations in Xi'an and Beijing carried out satellite-based CLT measurements. The results indicate that the ranging precision of the Xi'an and Beijing ground stations is approximately 4 mm, with a clock bias measurement precision of 22 ps.

This work marks a breakthrough in the engineering development of the pulsed laser time-frequency transfer system. As ground stations connect to high-performance atomic clock signals and sufficient measurement data is collected, the system will offer profound insights into the fields of time-frequency metrology, space geodesy, and fundamental physics research. It will enable the calibration and validation of microwave systems, a better understanding of clock behavior, comparison of clocks across remote observatories, and testing of Einstein’s gravitational redshift effect.