Advancements in Satellite-Ground Laser Time Transfer at the Shanghai Astronomical Observatory

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Outline

01 Technical overview

02 Research progress

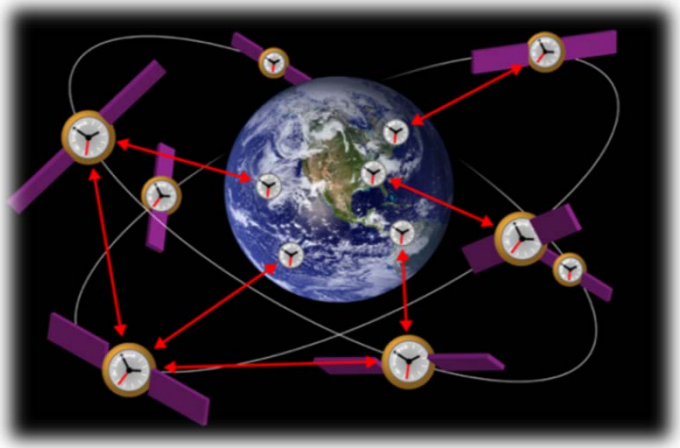
03 Earth-moon application

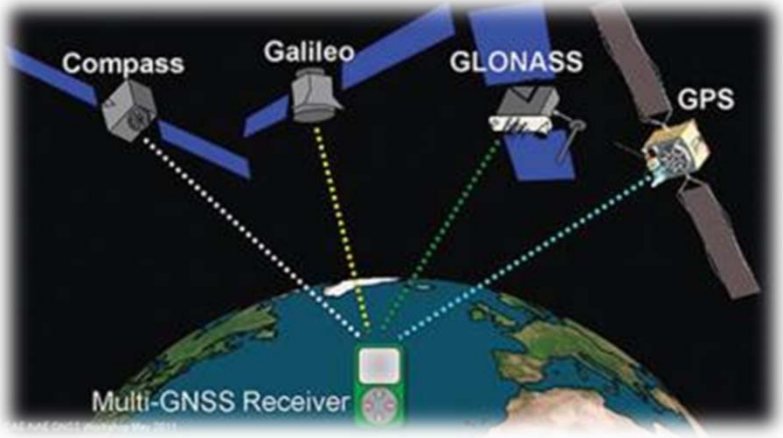
04 Summary

一、Technical overview

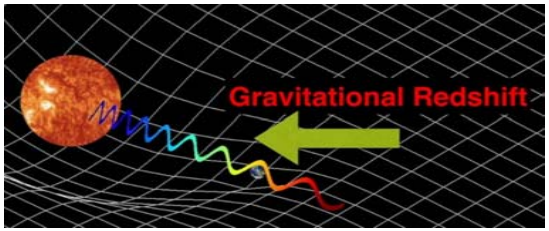
1.1 Background:

1) Time synchronization is the basis of modern positioning and navigation system, and the positioning accuracy is positively correlated with the time synchronization accuracy.





2) Basic scientific problems such as gravitational redshift, fine structure constant determination and dark matter detection can be studied in depth.



Optical Clocks and Relativity

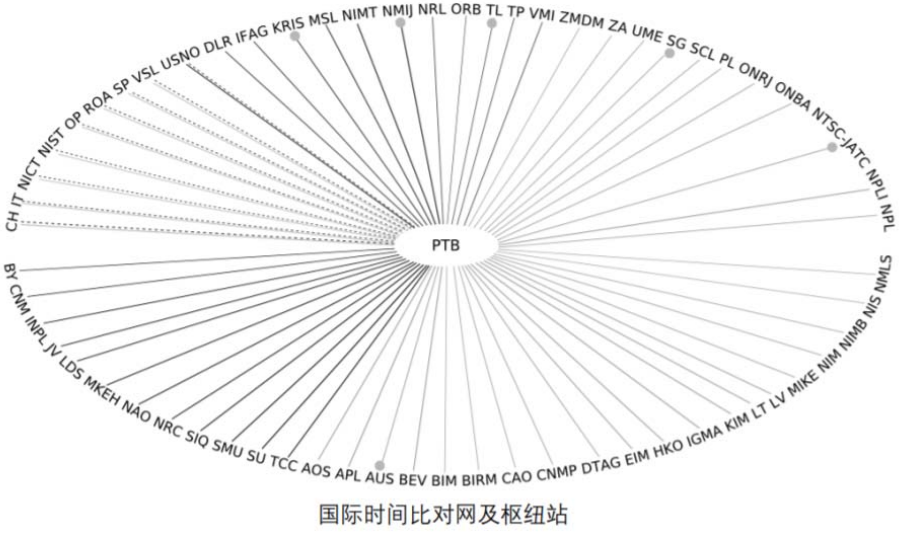
C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland

Observers in relative motion or at different gravitational potentials measure disparate clock rates. These predictions of relativity have previously been observed with atomic clocks at high velocities and with large changes in elevation. We observed time dilation from relative speeds of less than 10 meters per second by comparing two optical atomic clocks connected by a 75-meter length of optical fiber. We can now also detect time dilation due to a change in height near Earth's surface of less than 1 meter. This technique may be extended to the field of geodesy, with applications in geophysics and hydrology as well as in space-based tests of fundamental physics.

1、Technical overview

1.1 Background

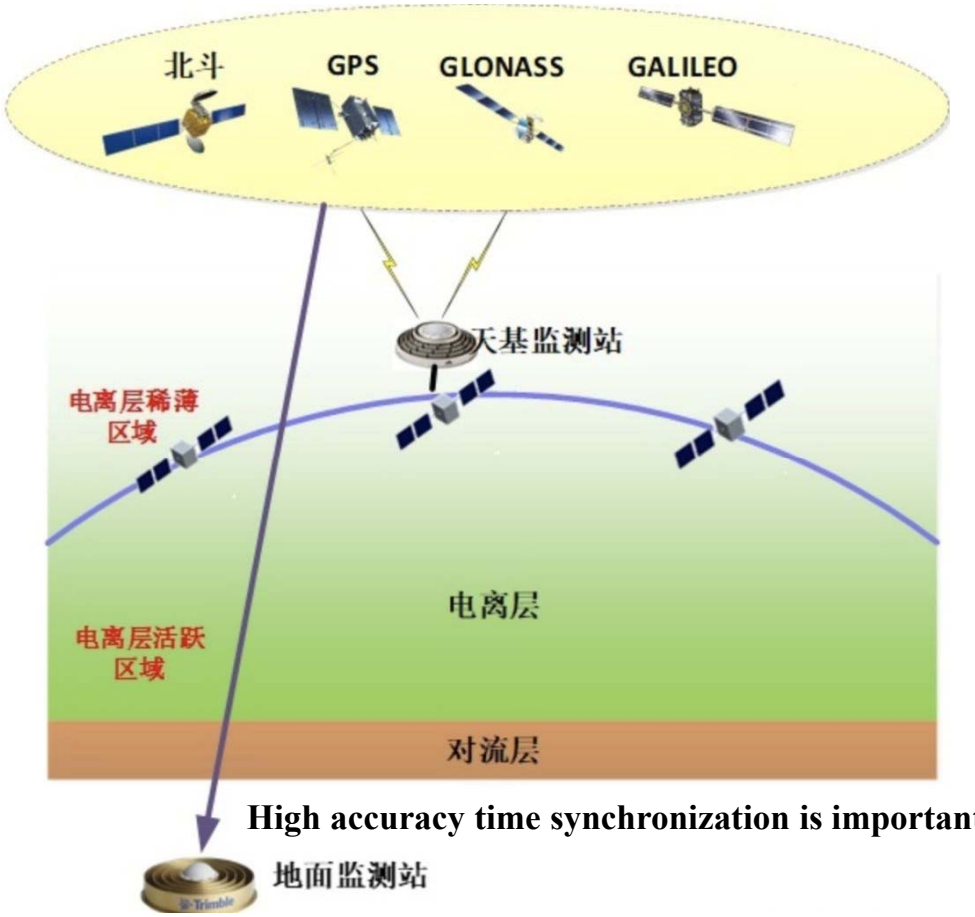
3) International Atomic time (TAI) comparison



国际时间比对网及枢纽站

International Atomic Time, or TAI, is derived from comparison data collected from more than 500 atomic clocks around the globe. The quality of this data is crucial, as it directly impacts the stability and accuracy of TAI.

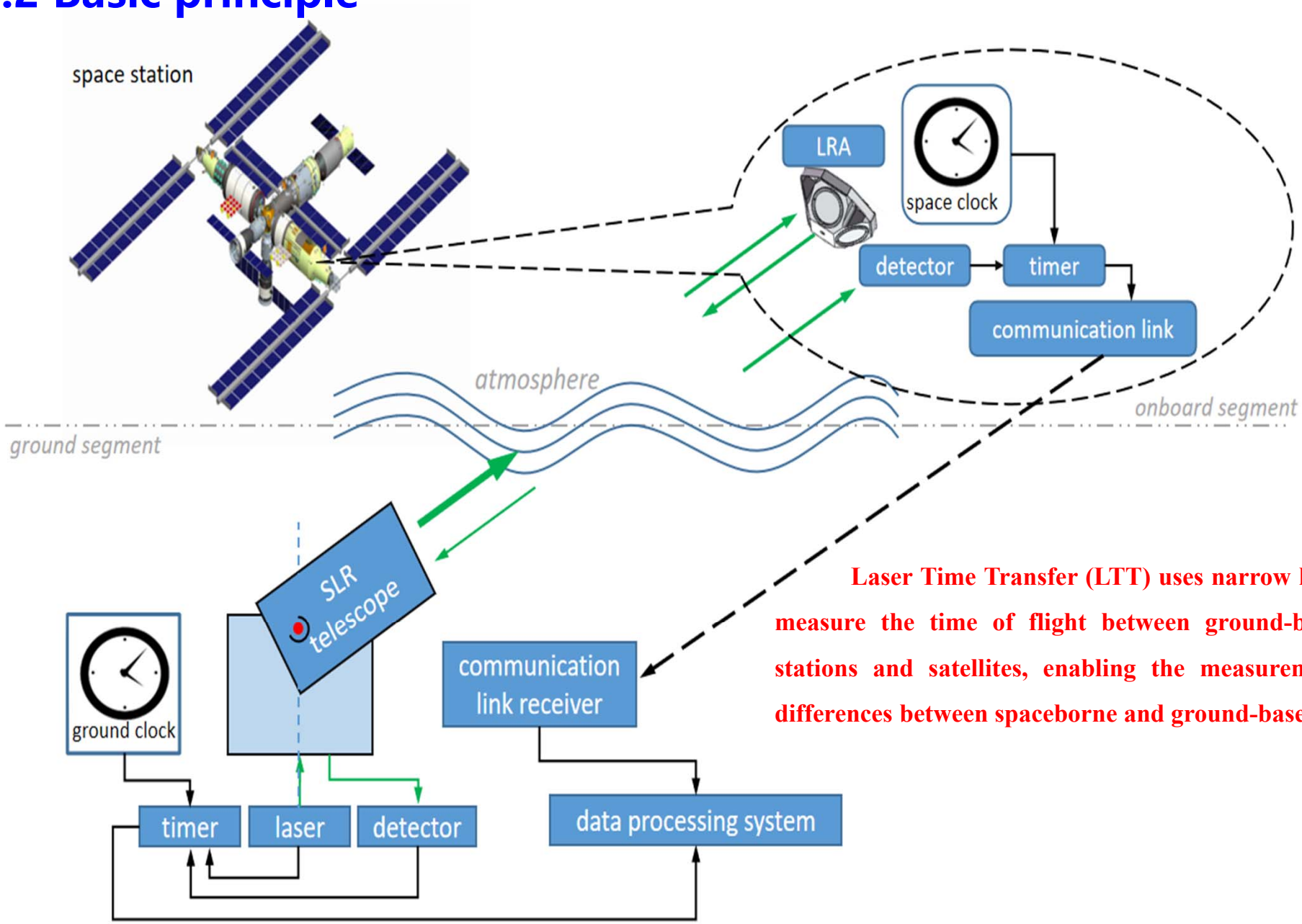
4) Low Earth Orbit-Enhanced Navigation Satellite



High accuracy time synchronization is important.

1、Technical overview

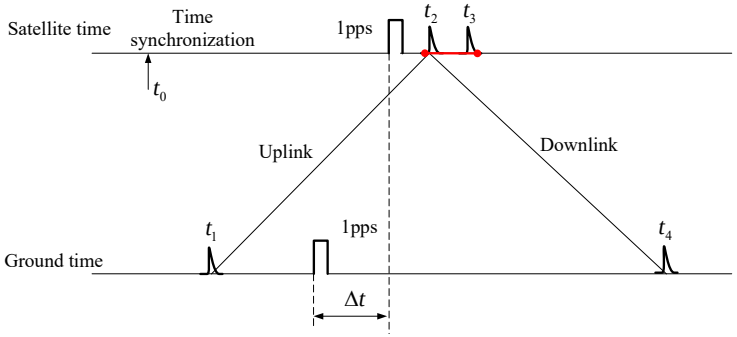
1.2 Basic principle



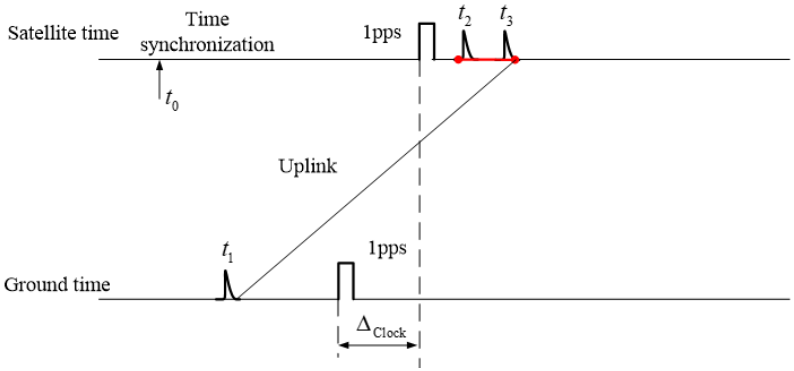
Laser Time Transfer (LTT) uses narrow laser pulses to measure the time of flight between ground-based ranging stations and satellites, enabling the measurement of clock differences between spaceborne and ground-based clocks.

1、Technical overview

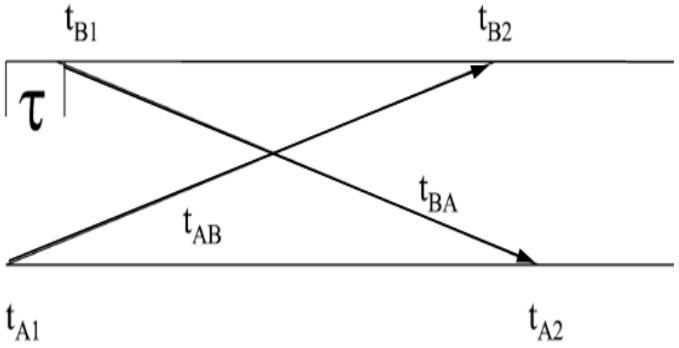
1.3 Working mode



	Traditional mode(based on the SLR/LLR)
Payload complexity	☺
Operating distance	☹(Earth-moon space，Laser energy attenuation R^{-4})
performance	☺ (<100ps)
Similar project	LTT、CLT、DRO，T2L2、ELT



	ono-way planetary laser ranging mode
Payload complexity	☺
Operating distance	☺ (Earth-moon space，Laser energy attenuation R^{-2})
performance	☹The measurement results are coupled with orbital errors.
Similar project	LRO



	two-way planetary laser ranging mode
Payload complexity	☺ +Laser+telescope+turntable+ etc
Operating distance	☺(Earth-moon space，Laser energy attenuation R^{-2})
performance	☹(>100ps)
Similar project	MLA、MOLA

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2、Research progress

1）LASSO(Laser Synchronization from Stationary Orbit)

LASSO allows intercontinental time transfer, as well as satellite clock monitoring, with a precision better than 100 picoseconds.

2）T2L2 (Time Transfer by Laser Link)

The T2L2 realized time transfers with a stability better than 3-4 ps over 30 s and an accuracy better than 100 ps.

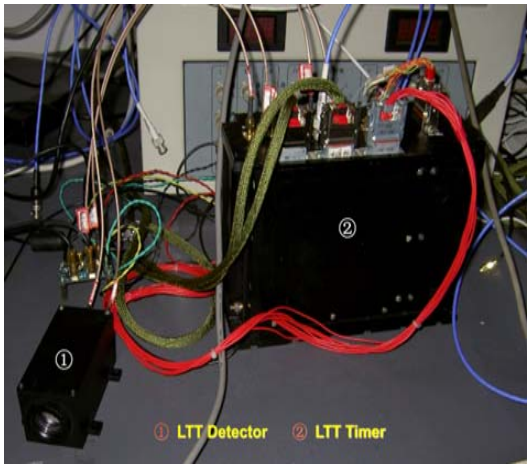
3） ELT(Europe Laser Timing)

The targeted accuracy (in CV) is 25ps and stability of 3ps at 300s of integration time.

Instrument	Accuracy	Detector (photon, ps)	Timer (ps)	Stability		Link
				1-shot (ps)	NP (ps)	
MLA	1 ns		200	500		1-way downlink
LRO	< 1 ns		200	360	165 / 5 s	1-way uplink
T2L2	< 100 ps	Multiple, 70	3	45–50	3–4 / 30 s	2-way (LRA)
LTT		Single, < 150	< 100	260	20 /500 s	id.
ELT	25 ps	Single, 10	<1	10	3 /300 s	id.
GPS (CV)	1–2 ns			5 ns (15')	1 ns /1 day	1-way

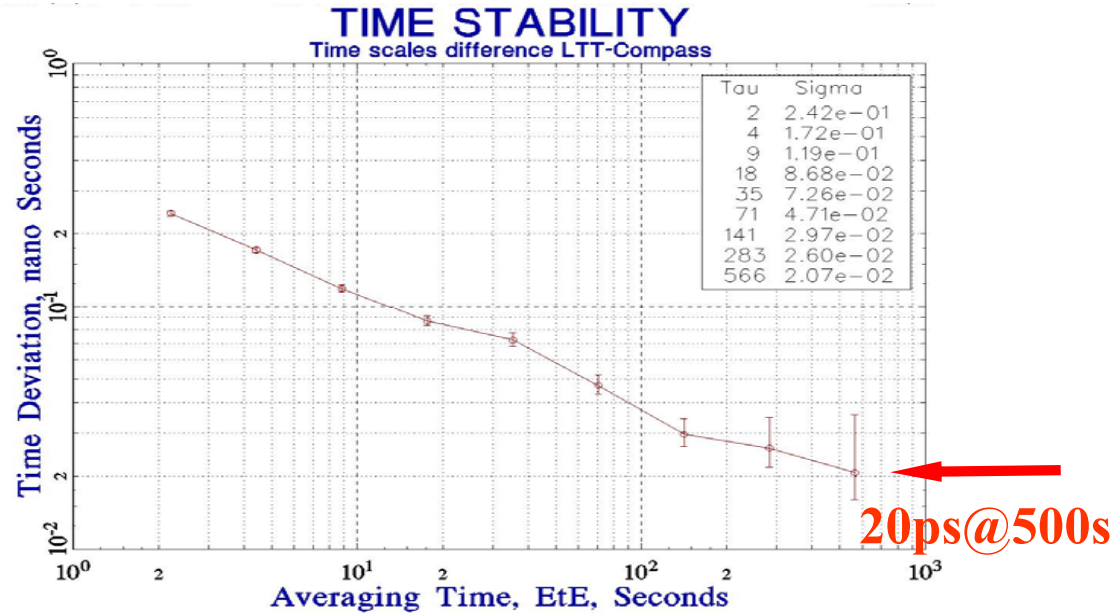
Exertier P, Belli A, Samain E, et al. Time and laser ranging: a window of opportunity for geodesy, navigation, and metrology[J]. Journal of geodesy, 2019, 93: 2389-2404.

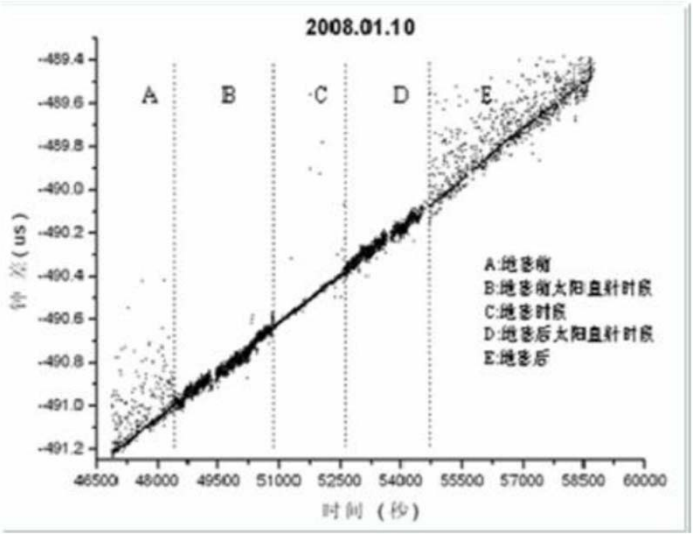
2、Research progress-LTT



Laser Time Transfer on Beidou is the first ground and satellite time synchronization system by laser ranging to navigation satellites. The whole system including the onboard instruments and ground SLR station was designed by the Shanghai Astronomical Observatory (SHAO).

2、Research progress-LTT

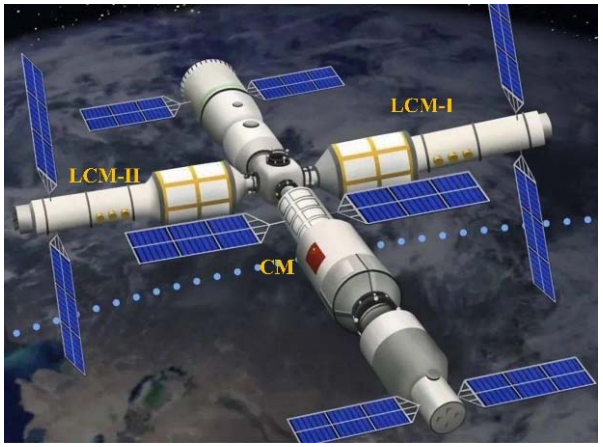




The LTT payloads were installed on Beidou MEO/IGSO satellites and launched on April 2007, August 2010, April 2011, and April 2012.

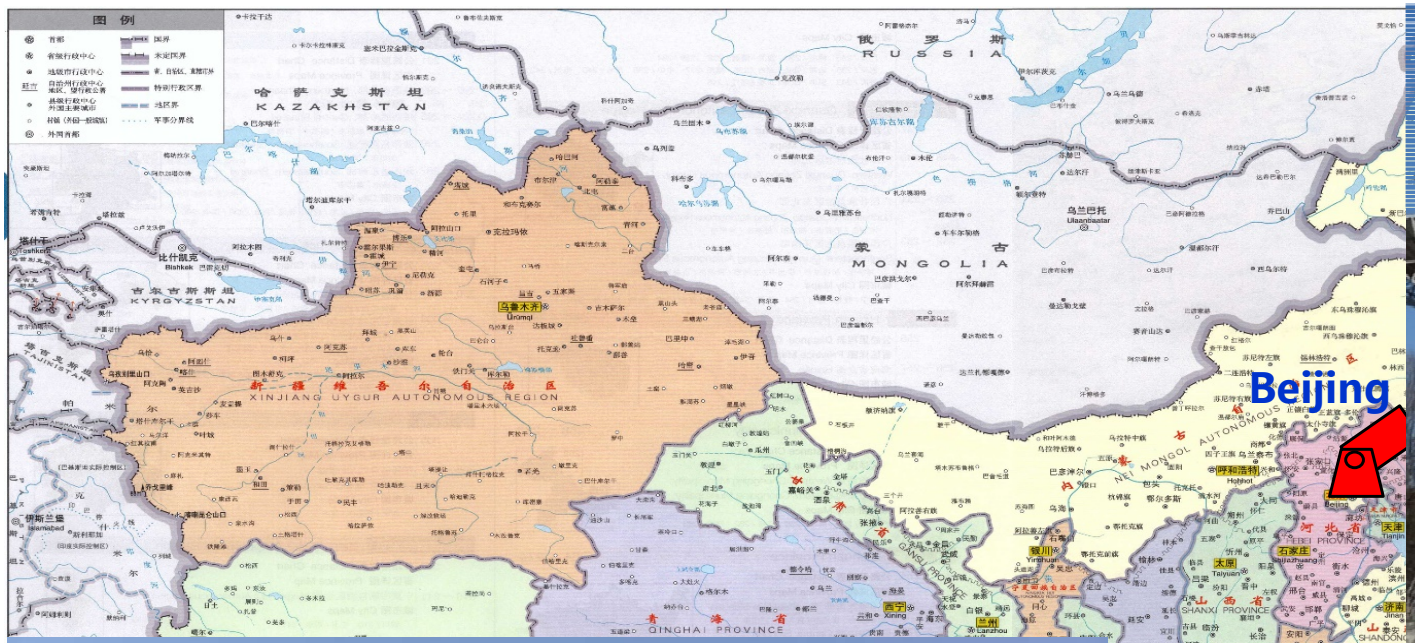
All the measurement of LTT experiments have a single-shot precision of around 300ps and a time stability of 20ps over a single session of 500s duration.

2、Research progress-CLT



The experiment module II of CSS equipped with the high-precision time-frequency rack was successfully launched in October 2022 and currently, the on-orbit testing experiments are ongoing.

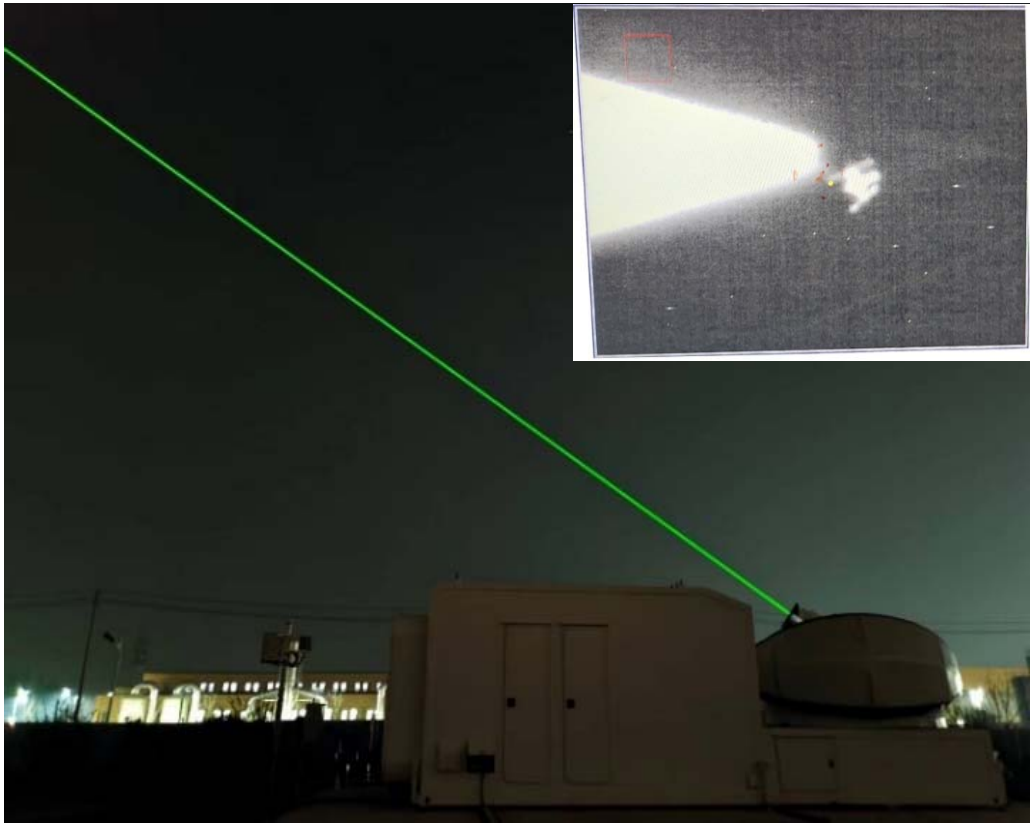
2、Research progress-CLT



- Receiving aperture 400mm
- Firing aperture 100mm
- Laser 532nm@10kHz
  >0.4mJ@30ps
- Laser emission time adjustment <10ns
- Stable reference clock
- Temperature control of detector, movable ground target, etc.

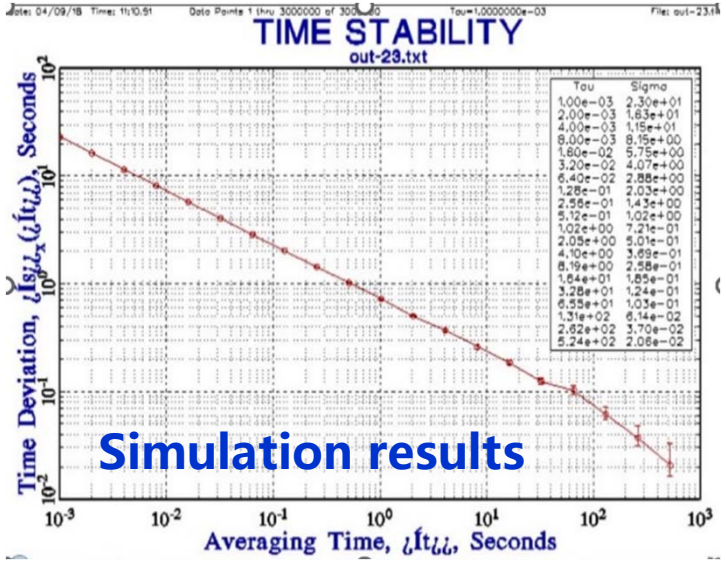
We have built two dedicated SLR stations to support the CLT experiments.

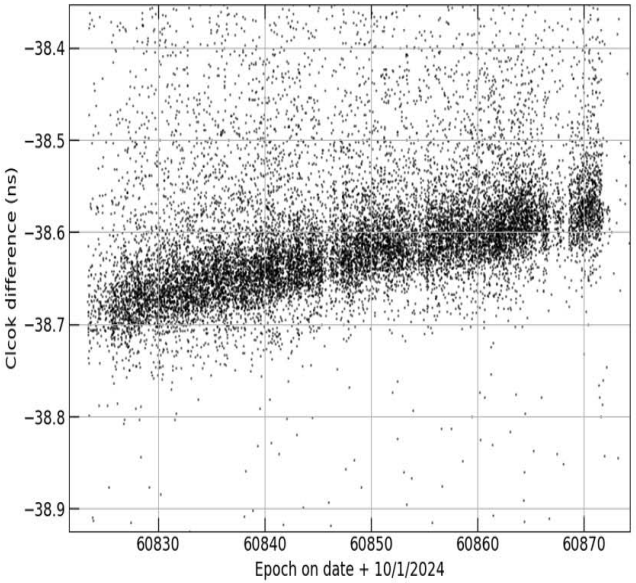
2、Research progress-CLT

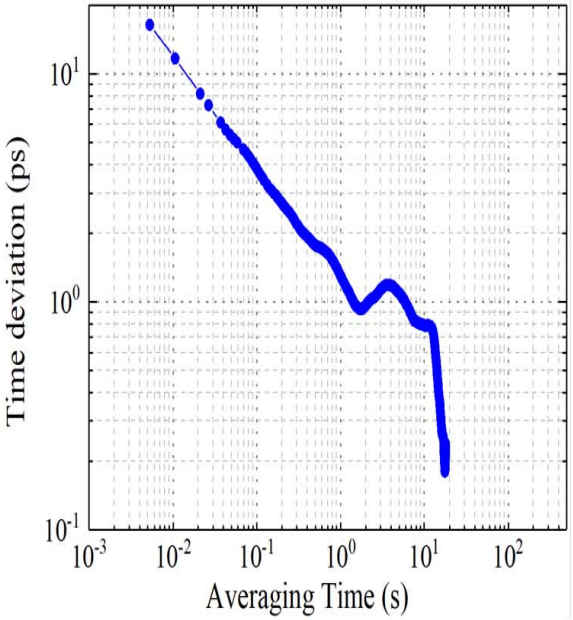


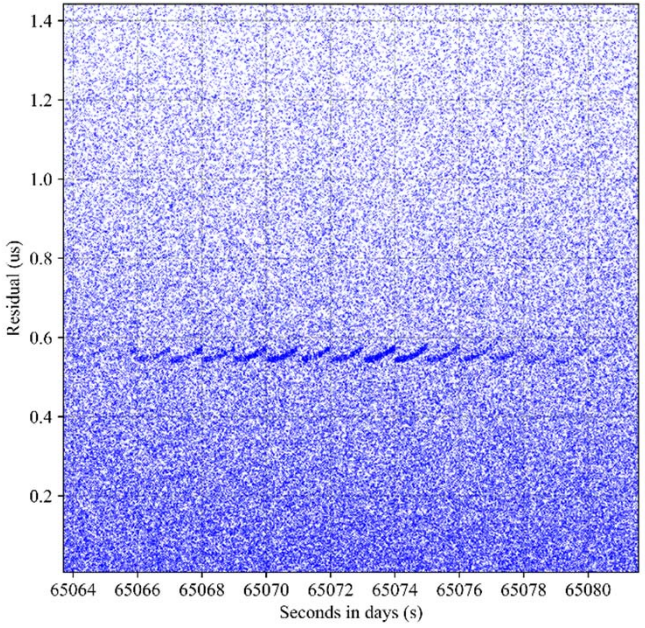
Picture of CLT payload captured by video camera on CSS

2、Research progress-CLT



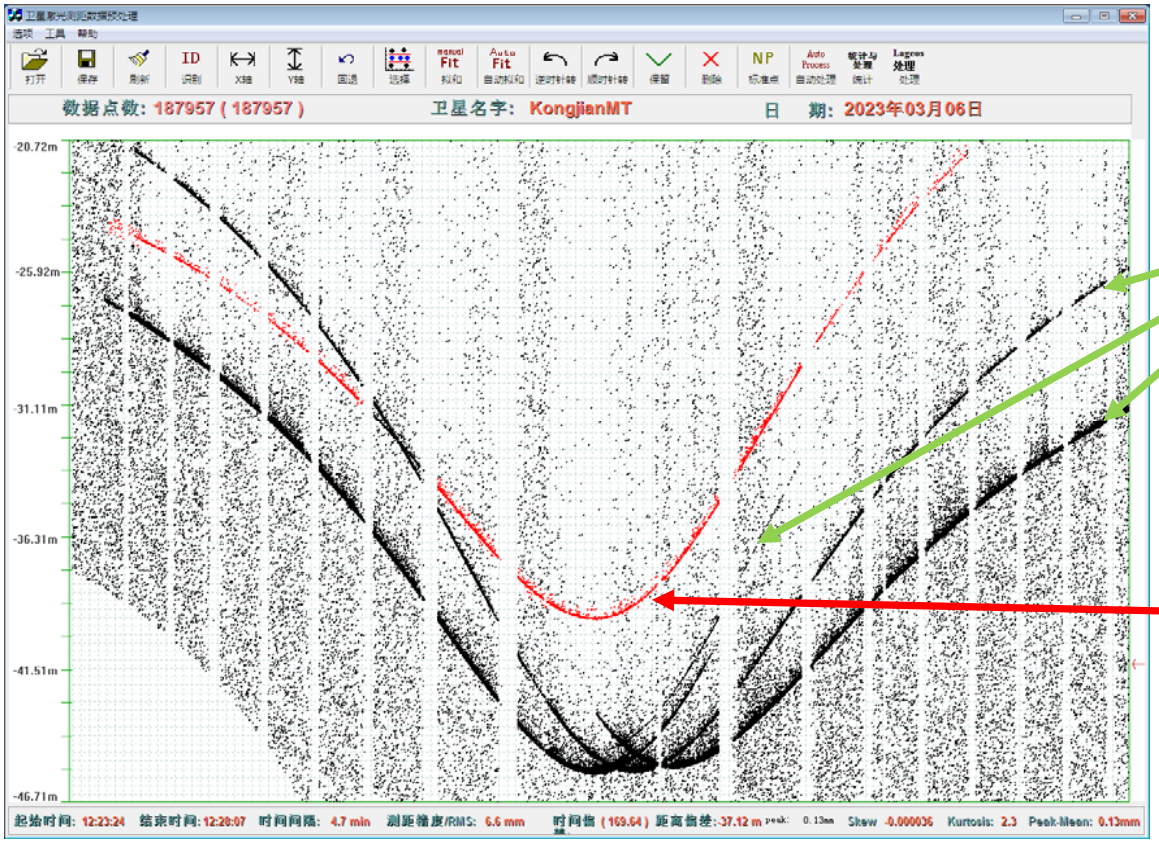


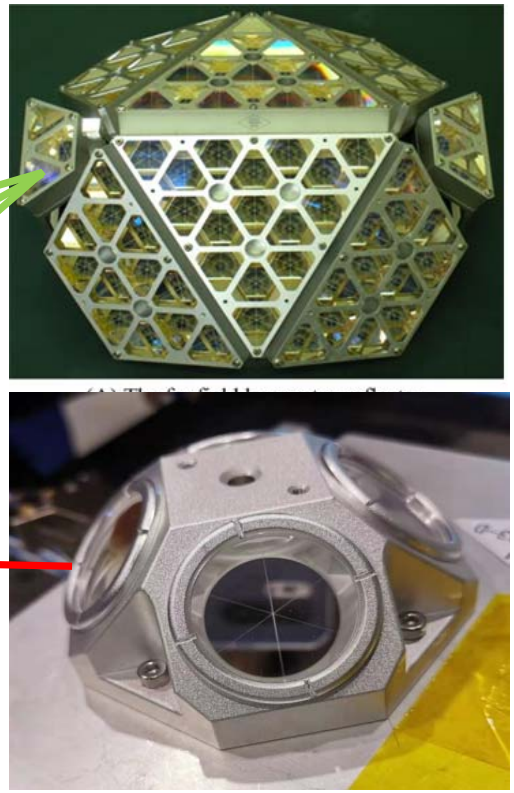




- The ground SLR station is equipped with a hydrogen clock and the onboard clock is a microwave clock .
- The measurement precision of the satellite-ground clock difference is better than 22 picoseconds, with a stability characterized by a TDEV of 0.2 picoseconds over 20 seconds. For detailed results, please refer to my conference poster.
- The simulation results are basically consistent with the measurement data.

2、Research progress-CLT



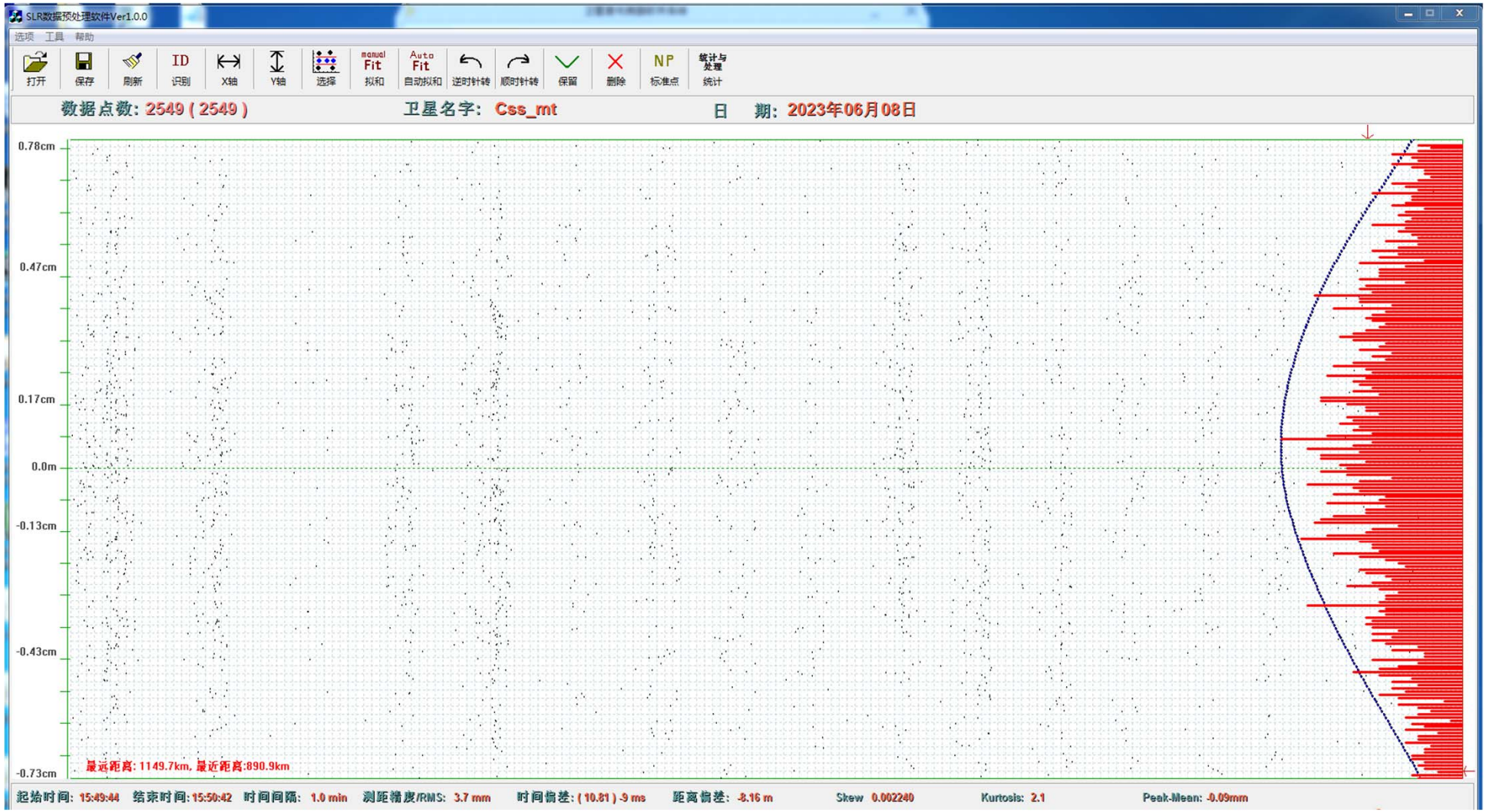


The Lidar CCRs are served for CSS spacecraft's rendezvous activities.

In the laser time transfer of China's space station, there is a complex issue of echo interference from the lidar CCRs.

Several methods (including relative positioning of CCRs, signal data precision) are adopted to identify the signal from CLT CCR.

2、Research progress-CLT



The precision of laser ranging of CLT CCR is 3-4mm

2、Research progress-CLT

		Laser time transfer in Beidou	Laser time transfer in CSS
Performance parameter	precision	300ps	<30ps
	Time deviation	20ps@500s	0.1ps@300s， 1ps@1day
	Repetition rate	1Hz/20Hz	10kHz
Detector	Detector type	Single photon	Single photon
	precision	150ps	30ps
	field of view	30°	>110°
Event timer	precision	100ps	<10ps
	Repetition rate	20Hz	~ 10kHz
laser retroreflector array		Flat plate design, strong reflection ability but large measurement error	a pyramid shape, similar to that of the CHAMP satellite

[1] Wu Z, Geng R, Tang K, et al. Performance of laser time-frequency transfer system in China Space Station[J]. Acta Optica Sinica, 2024.
[2] Geng R, Wu Z, Huang Y, et al. A complete analysis of the link uncertainty budget for pulsed laser time transfer on China space station[J]. Advances in Space Research, 2024, 73(5): 2548-2566.
[3] Meng W, Zhang H, Huang P, et al. Design and experiment of onboard laser time transfer in Chinese Beidou navigation satellites[J]. Advances in Space Research, 2013, 51(6): 951-958.

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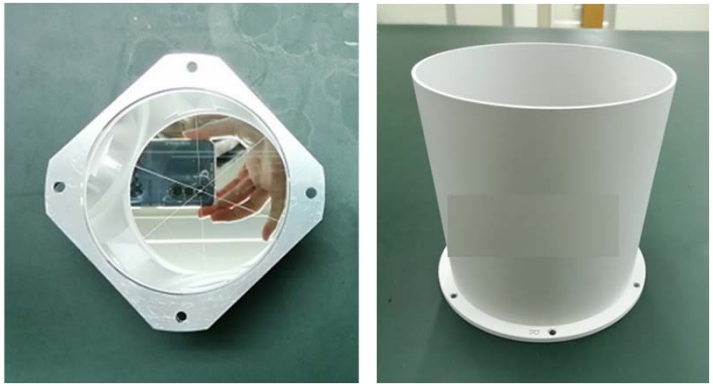
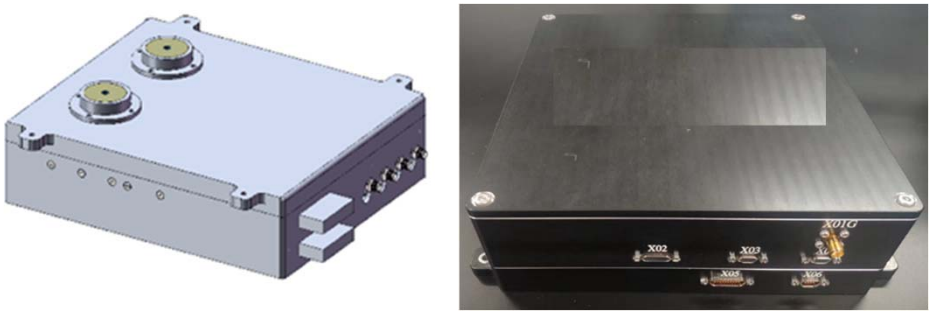
3、EARTH-MOON APPLICATION

lunar orbit satellite



100-millimeter-sized CCR



Laser time transfer payload

The lunar satellite is equipped with a 100-millimeter-sized CCR and a laser time transfer payload:

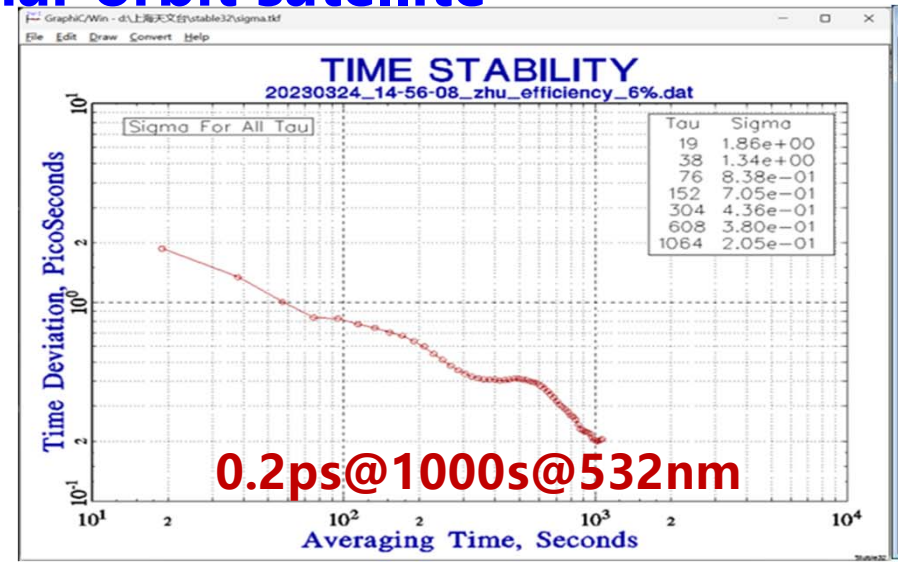
- High precision lunar laser ranging (centimeter-level) and time transfer (hundred-picosecond level) at the Earth-Moon scale can be conducted.
- It can be used for orbit calibration and to enhance our understanding of clock behavior in the Earth-Moon system.

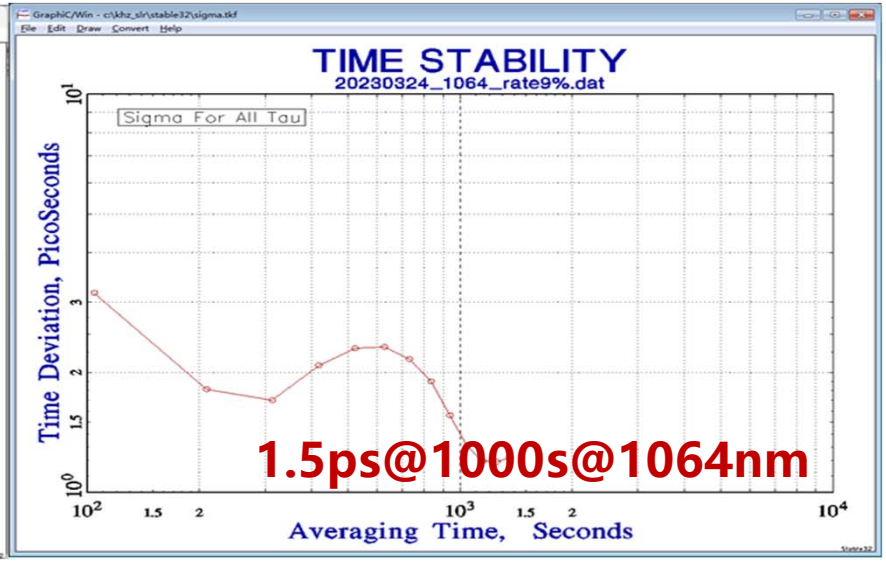
3、EARTH-MOON APPLICATION

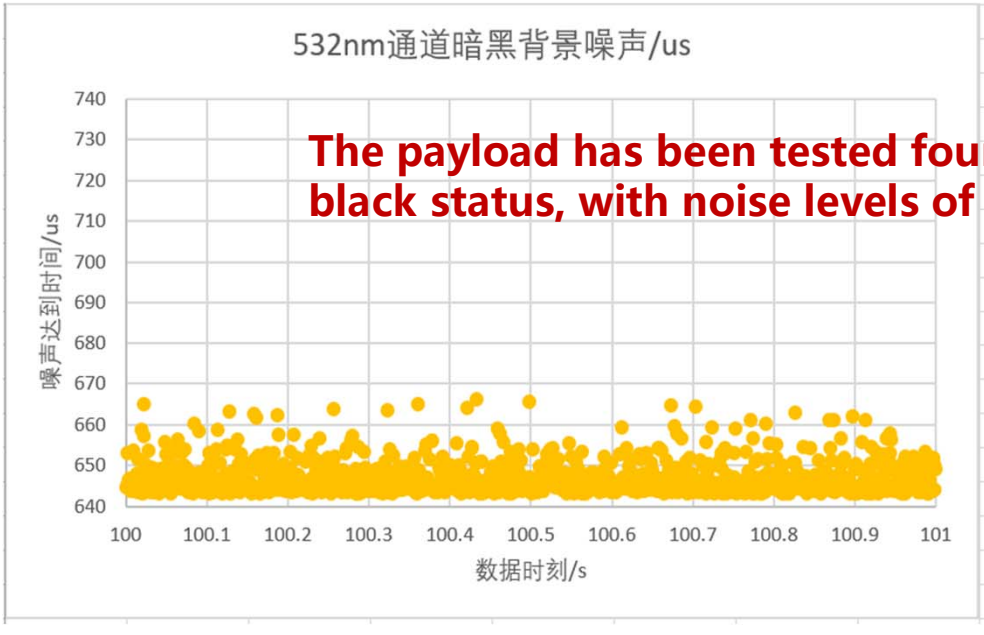
	iterms	Parameter achieved
1	The receiving area diameter	φ3.7mm CA(optic lens 532nm) φ100μm (sensitive area 1064nm)
2	FOV （full angle）	~2.5° for 1064nm channel ~1° for 532nm channel
3	Detector precision	50ps@1064nm 27ps@532nm
4	Timer precision	8ps

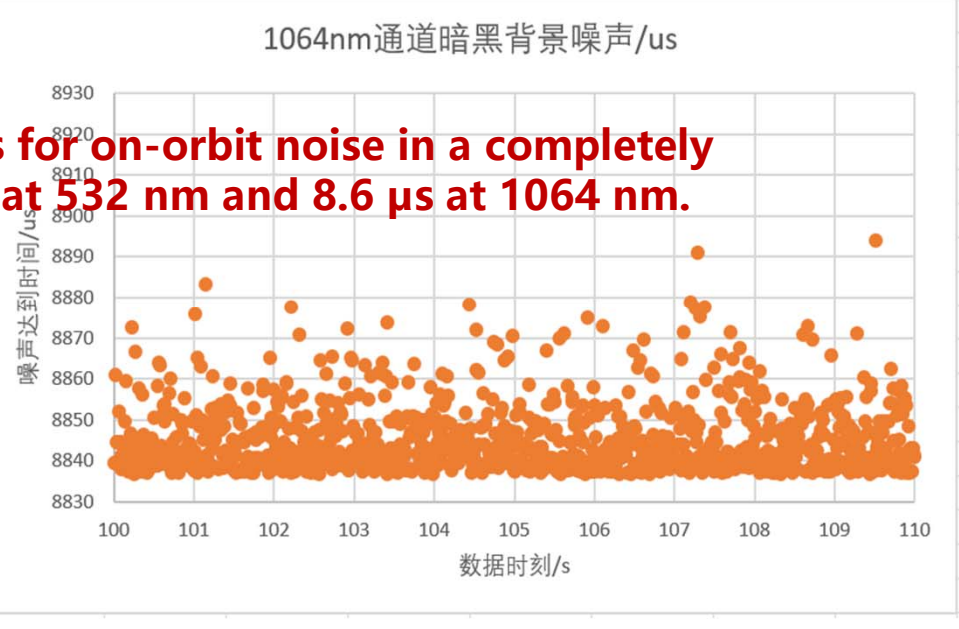
3、EARTH-MOON APPLICATION

lunar orbit satellite









The payload has been tested four times for on-orbit noise in a completely black status, with noise levels of 3.9 μs at 532 nm and 8.6 μs at 1064 nm.

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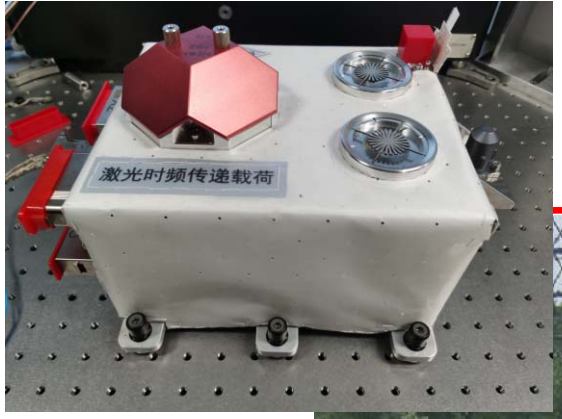
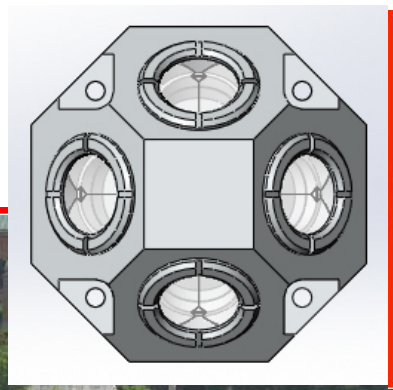
4、SUMMARY

1. The Shanghai Astronomical Observatory has developed comprehensive capabilities for space-ground laser time transfer, including ground observation stations, spaceborne laser retroreflectors, and laser time transfer payloads.
2. The laser time transfer missions for the BeiDou system and the Chinese Space Station have been successfully completed, achieving a single-pass precision of better than 22 ps and a time deviation stability (TDEV) of 0.2 ps at 20 seconds.
3. Currently, the Shanghai Astronomical Observatory is undertaking lunar space time transfer and ranging missions to support the establishment of an Earth-Moon space-time reference.





Thank you for your attention !

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