Precise Generation and Transfer of Time and Frequency in NTSC

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23 October, 2018

Content

- **Time science activities in NTSC**

  Atomic frequency standards (Cs fountain, Cs beam clock)

  and Sr optical clock (towards future SI second definition)

  Astronomical time observation (UT1 measuring, Pulsar Timing Obs)

  Timekeeping (UTC realization)

  T/F signal dissemination service (BD CV, long & short wave, CAPS,

  fiber link ...)

- **Important projects for NTSC**

  Precision Land-Based Time Service System

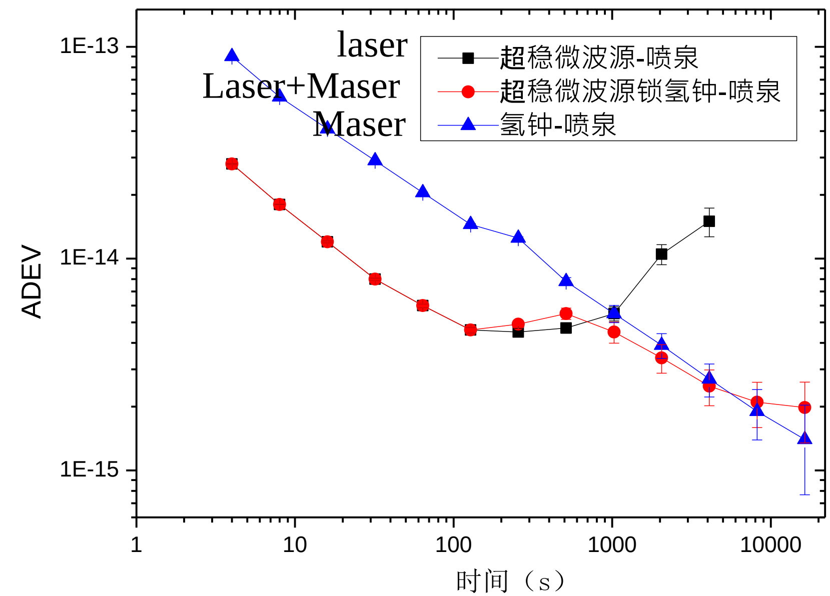
  Precision Time-Frequency system in China Space Station

(1) Development of Cs fountain clock

Cs fountain clock	Frequency stability	Frequency uncertainty
IT-CSF2	$1.3\times10^{-13}\tau^{-1/2}$	0.2×10^{-15}
NICT-CSF1	$2.8\times10^{-13}\tau^{-1/2}$	1.2×10^{-15}
NIST-F2	$1.3\times10^{-13}\tau^{-1/2}$	0.11×10^{-15}
NPL-CsF2	$1.6\times10^{-13}\tau^{-1/2}$	0.23×10^{-15}
PTB-CSF1	$2.0\times10^{-13}\tau^{-1/2}$	0.32×10^{-15}
PTB-CSF2	$3.5\times10^{-14}\tau^{-1/2}$	0.21×10^{-15}
SYRTE-FO1	$1.6\times10^{-14}\tau^{-1/2}$	0.34×10^{-15}
SYRTE-FO2	$1.6\times10^{-14}\tau^{-1/2}$	0.21×10^{-15}
SYRTE-FOM	$5.0\times10^{-14}\tau^{-1/2}$	0.60×10^{-15}
NIM5	$1.4\times10^{-13}\tau^{-1/2}$	0.9×10^{-15}
NTSC-F1	$5.0\times10^{-14}\tau^{-1/2}$	0.6×10^{-15}

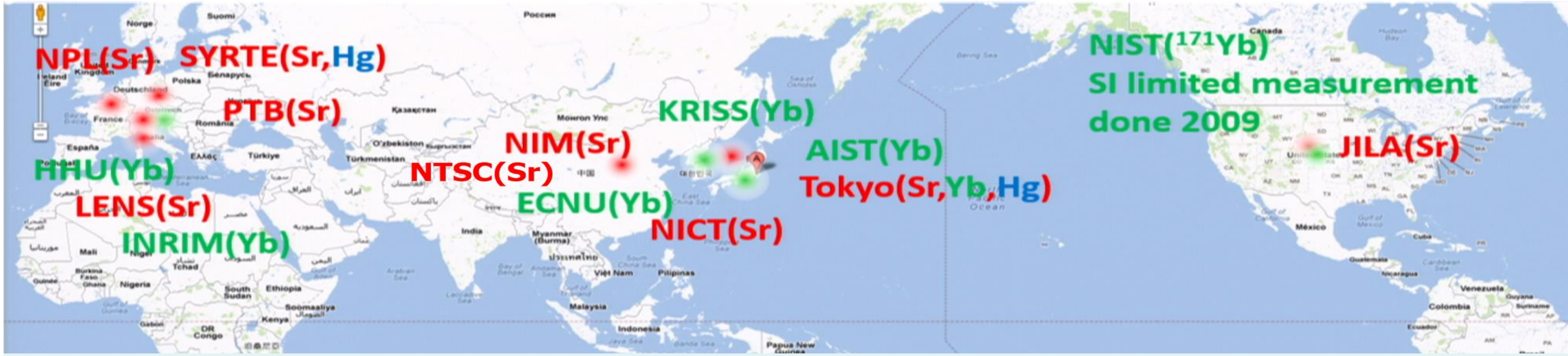
Cesium fountain clock NTSC-F1

- **2D MOT cold atom beam loading （atom beam flux ~2E9 atoms/s）**
- **Precise measurement of collisional shift by adiabatic transition**
- **Low-noise microwave generation via stable lasers （9.2GHz：7E-15@1s, 3E-15@10s；frequency stability improved by 4 times, τ<2000s； SYRTE/PTB）**
- **Once open, continues >30days**



	source	Shift E-15	Uncertainty E-15
1	2nd order Zeeman	56.7	0.14
2	Collisional shift	36.0	0.28
3	BBR	-15.2	0.22
4	Gravity shift	52.8	0.10
5	□w leakage	0	0.3
6	Cavity phase shift	0	0.5
	sum	130.3	0.6

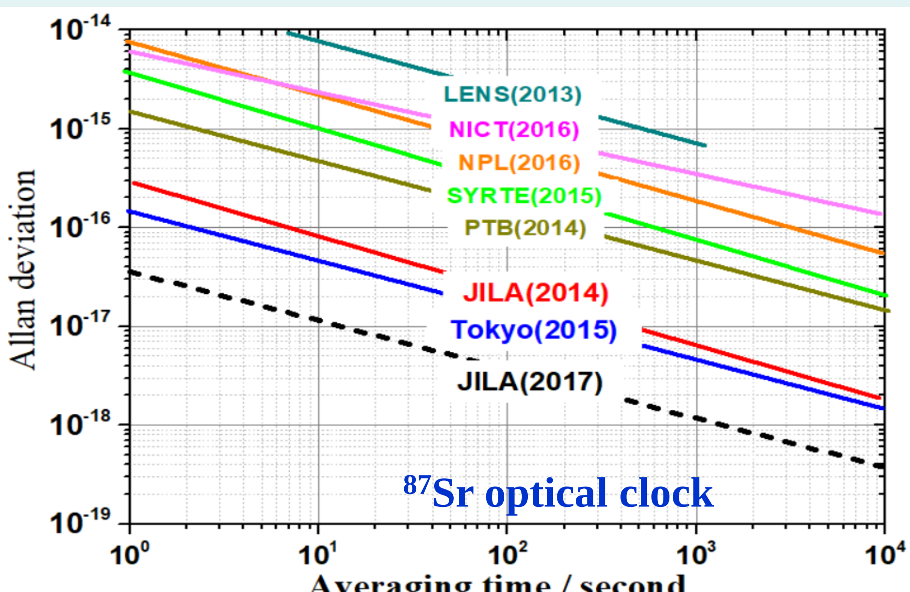
(2) Optical clocks based on neutral atoms

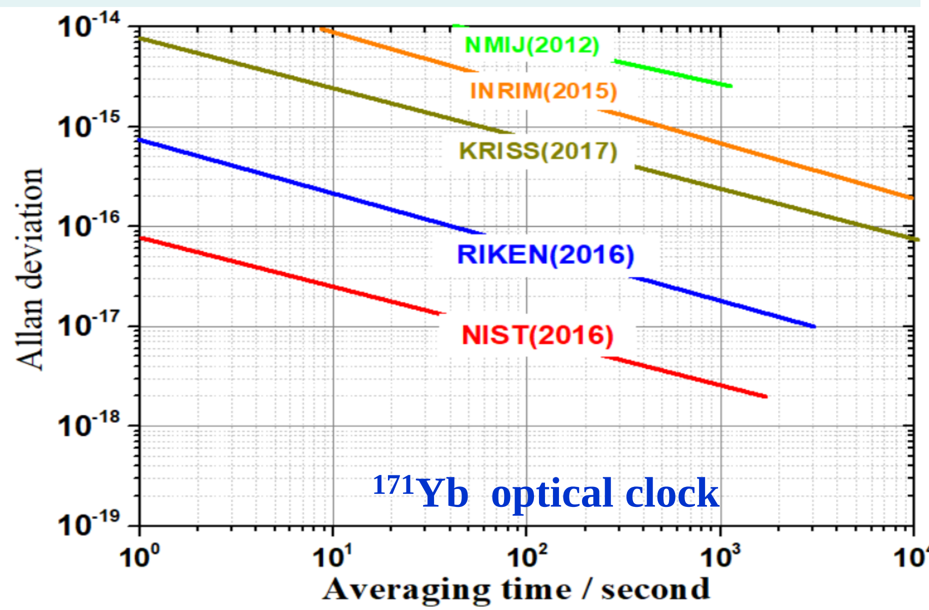


Uncertainty evaluation: 8 groups @ ^{87}Sr clock, 5 groups @ ^{171}Yb clocks

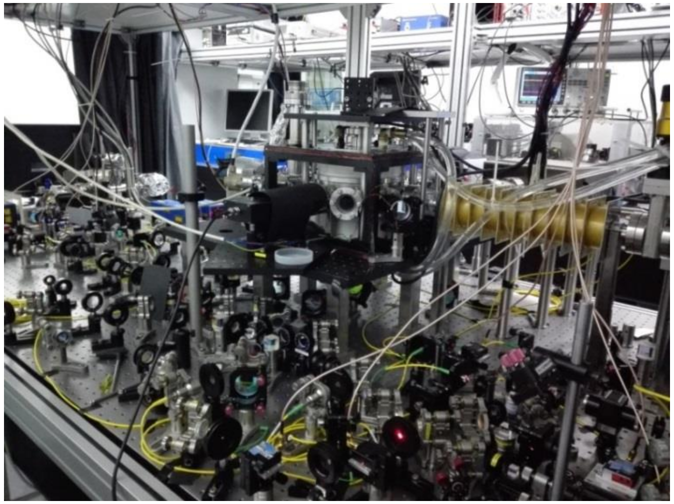
The overall measurement uncertainty is at the order of 10^{-17} ～10^{-18}.

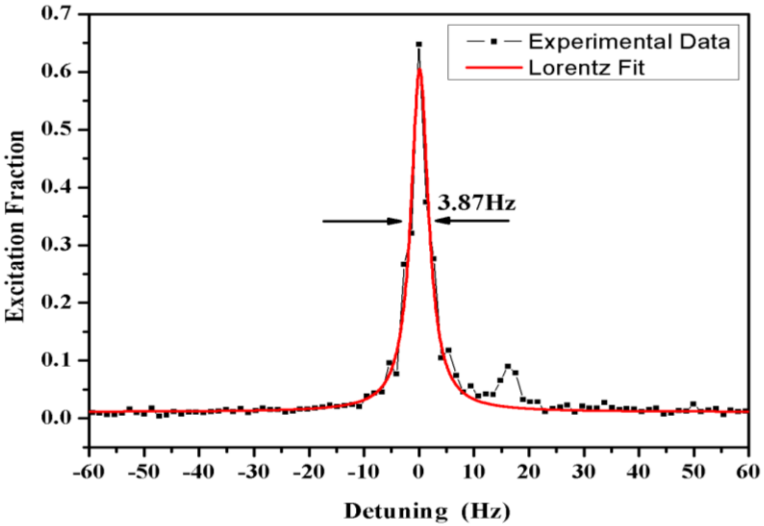
Ye Jun@JILA： total uncertainty 2.1×10^{-18}、independent clock stability 2.2×10^{-18} @10000s （2015） ; measurement precision 5×10^{-19} （2017）



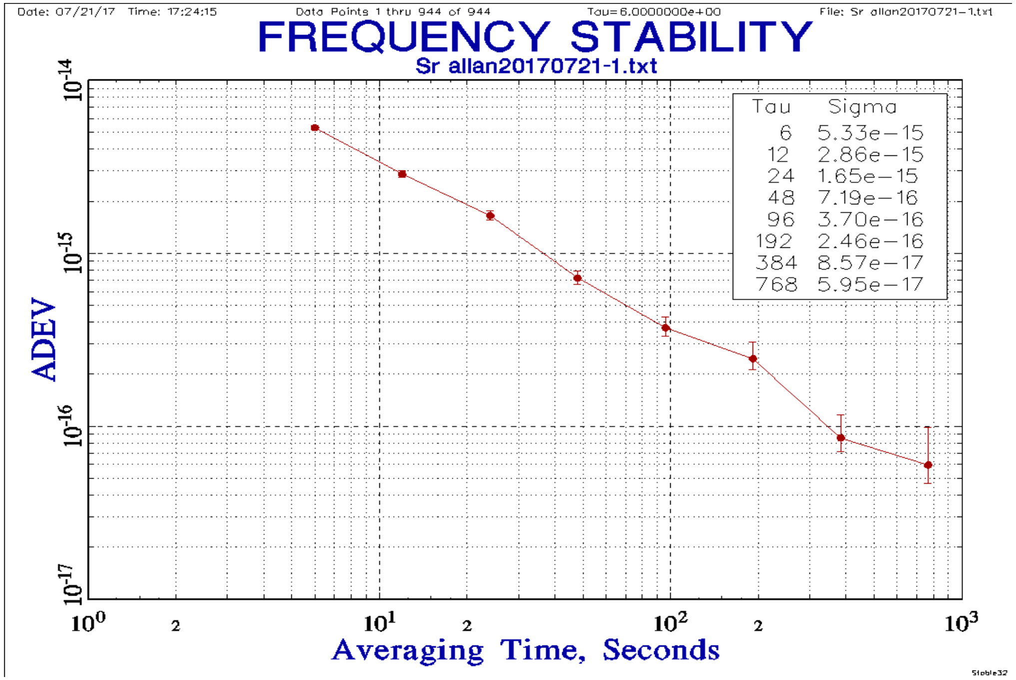


^{87}Sr optical lattice clock





spin polarized spectrum of clock transition



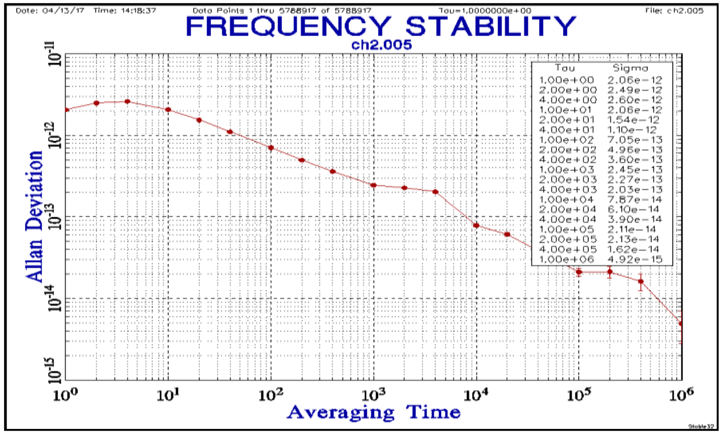
Frequency stability of the clock (in-loop)

- **Stability: 5×10^{-15}/6s, 6×10^{-17}/800s**
- **Preliminary evaluation of uncertainty: ~10^{-16}**
- **Next step: BBR shift**

Acta Physica Sinica,2018,67(07):84-91.

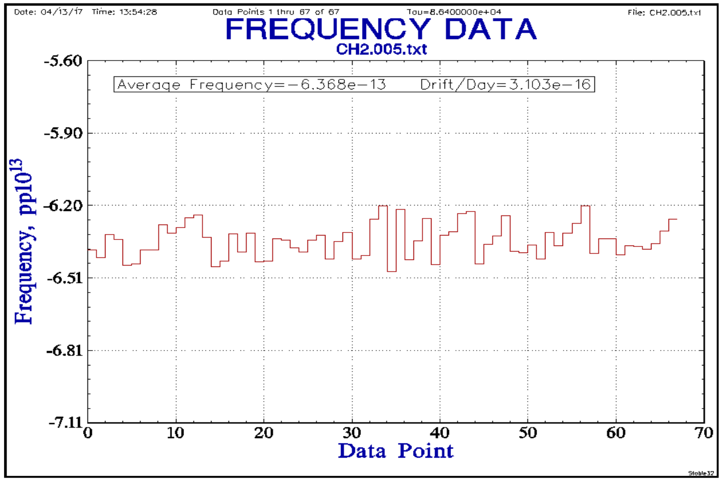
(3) Optically pumped Cs beam clock

- **The first commercial optically pumped cesium beam clock (Cooperation with Spaceon, CETC 12, NTSC)**
- **Evaluation on 6.13. 2017 ：better than 5071A standard product**
- **Applied in Navy's new timekeeping system, continuous operation > 1.5 year**
- 5 clocks tested for time keeping system in NTSC



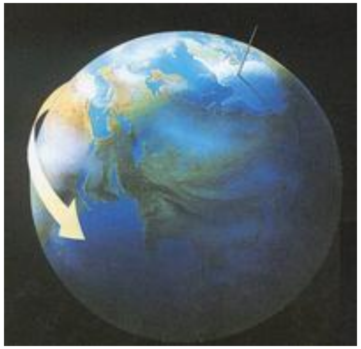
Frequency stability（10000s）
BSNC 7.8E-14、NIM 1.1E-13

Frequency drift
BSNC 3.1E-16/d、NIM 5.4E-16/d



Frequency accuracy
BSNC 6.4E-13、NIM <1E-12

(4) Universal Time(UT1)



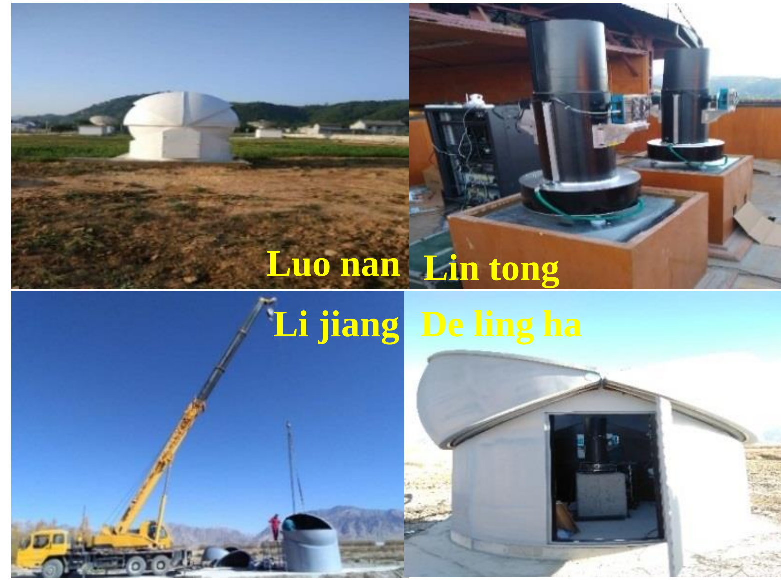
- **The universal time(UT1) is a time scale based on the natural rotation of the earth**
- **UT1 is most important for all the applications that need to convert the coordinate relationship between the ground and the space target, such as space exploration, satellite navigation…**
- **UT1 is the fastest, the biggest, the most difficult to measure and the most difficult to predict in all 4 Earth Orientation Parameters(EOP)**
- **Since 1991 there was no regular UT1 measurement in China**

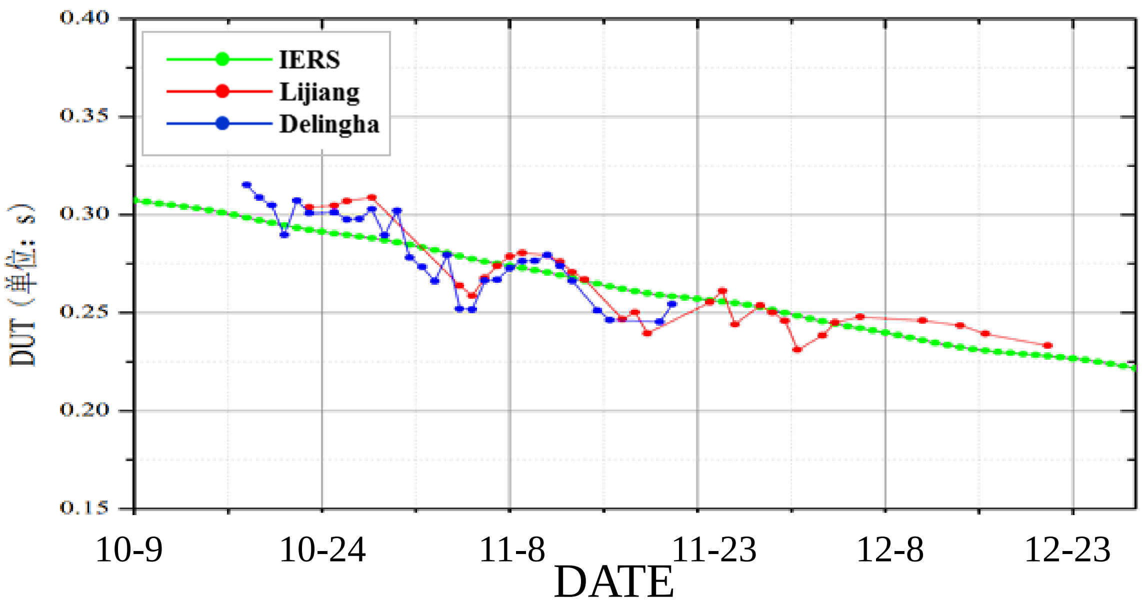
The measurment of UT1

A joint UT1 measurement system **is under construction by NTSC**

1. Zenith telescopes

- **6 station in Luonan, Lintong, Lijiang, Delingha, Kashi and Changchun**
- **Test observation started**
- **preliminary compliance: 2ms**

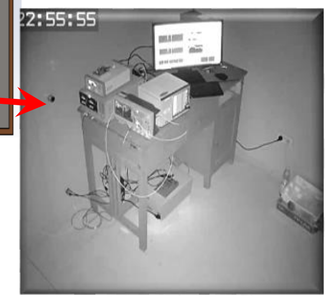




UT1 measurement with Giant-optic Gyro

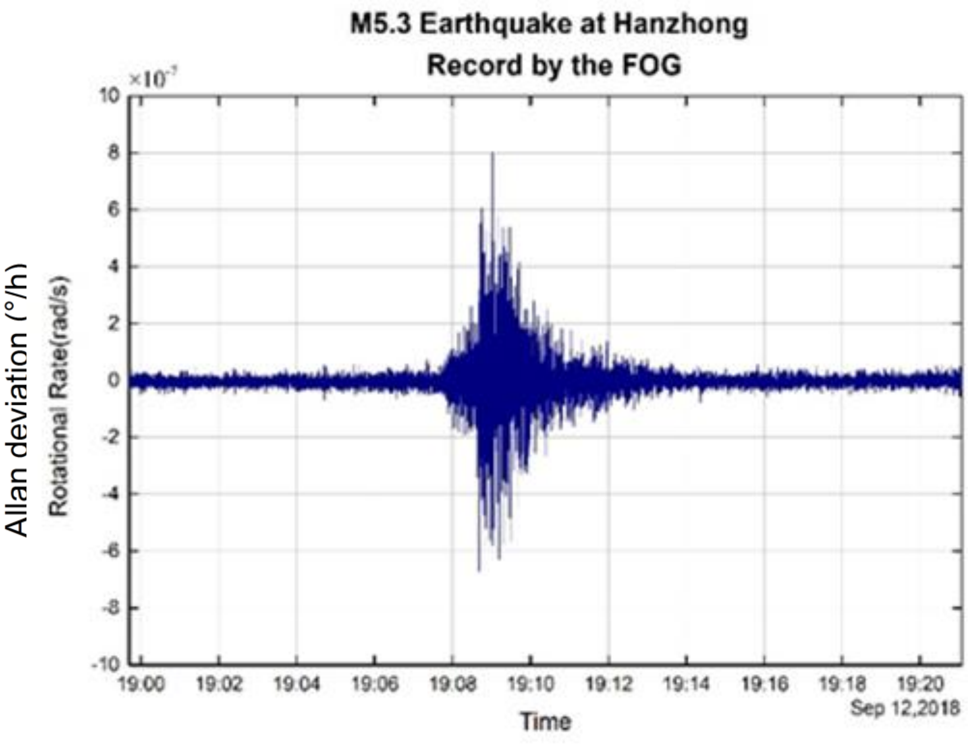
Giant-optic Gyro

- Proof-of-principle research
- Key technique
- Cooperation with Peking Uni.



Gyro station @ Pucheng, Xi'an

Gyro lab & Control



Temperature drift: 0.017 ºC/d (0.004 ºC/d@G-ring)

Tiltmeter drift : 0.032 "/d (0.017 "/d@G-ring)

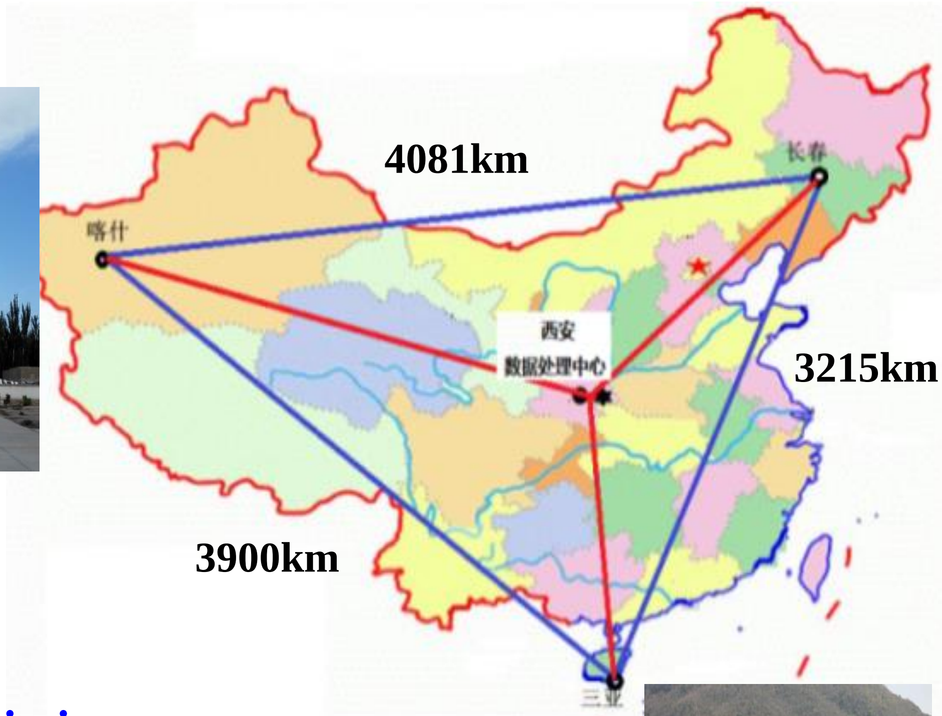
$\Phi \approx 0.4$ m, L=30 km,

- The recorded angle random walk: 14×10^{-6} º/ $\sqrt{h}$!

  Bias drift ~ 5×10^{-5} º/h, approaching the best FOG (Honeywell, ~ 1.6×10^{-5} º/h)

The measure of UT1

- We developed the first VGOS (VLBI Global Observation System) system in China and carried out the high-precision UT1 measurement
- 3 stations (Sanya, Changchun and Kashi) and a data center (Xi'an)



The preliminary measurement accuracy of the UT1 is 0.05ms

Cooperation with
上台、新台、长春人卫站、
中电39所和16所等

The measure of UT1

- **We developed the first VGOS (VLBI Global Observation System) system in China and carried out the high-precision UT1 measurement**
- **3 stations (Sanya, Changchun and Kashi) and a data center (Xi'an)**

Recent Intensive mode (KS-JL baseline) measurement of UT1

Observation	Posti-Prior（μs）	Std.（μs）	Abs(UT1-UTC)（s）	NTSC-IERS final（μs）
2018.6.12	196.6	21.2	0.0707166	-8.4
2018.6.13A	-72.0	33.8	0.0699009	49.9
2018.6.13B	4.4	39.9	0.0699773	-26.5
2018.7.24C	49.2	27.3	0.069227	29.4

(5) Pulsar Timing Obs System

Overview:

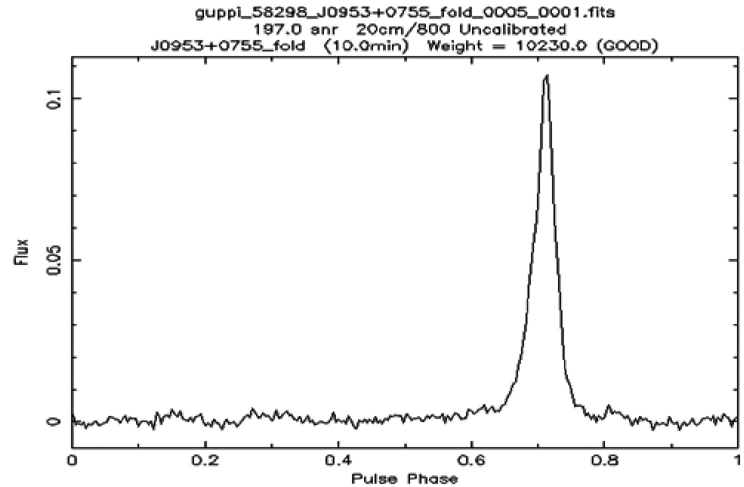
- 40m Radio Telescope
- L-band: 1.1-1.75GHz

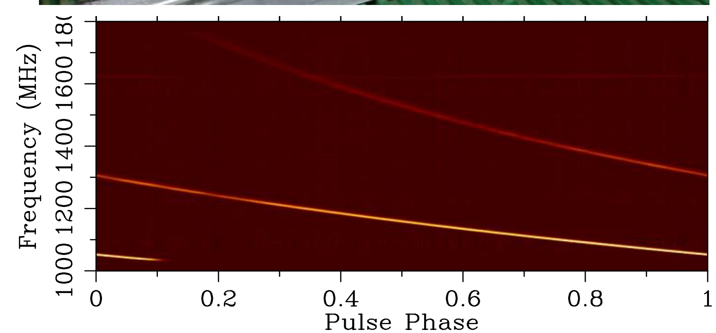
Pulsar Instrument development:

- FPGA+GPU
- Obs Mode: search, timing
- Incoherent dedispersion: done
- Coherent dedispersion: in progress
- Specifications close to NRAO's DIAS

On-going researches:

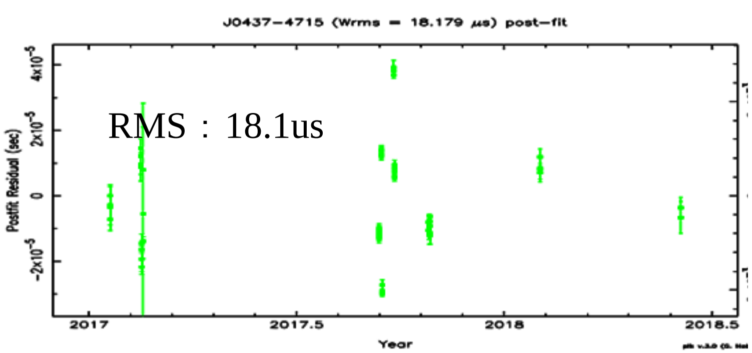
- Pulsar timescale: ~5 millisecond pulsars, Crab pulsar, etc
- Pulsar glitch and emission mechanism
- Pulsar scintillation
- Fast Radio Burst search
- Collaborations with FAST: Pulsar search, Giant Pulses



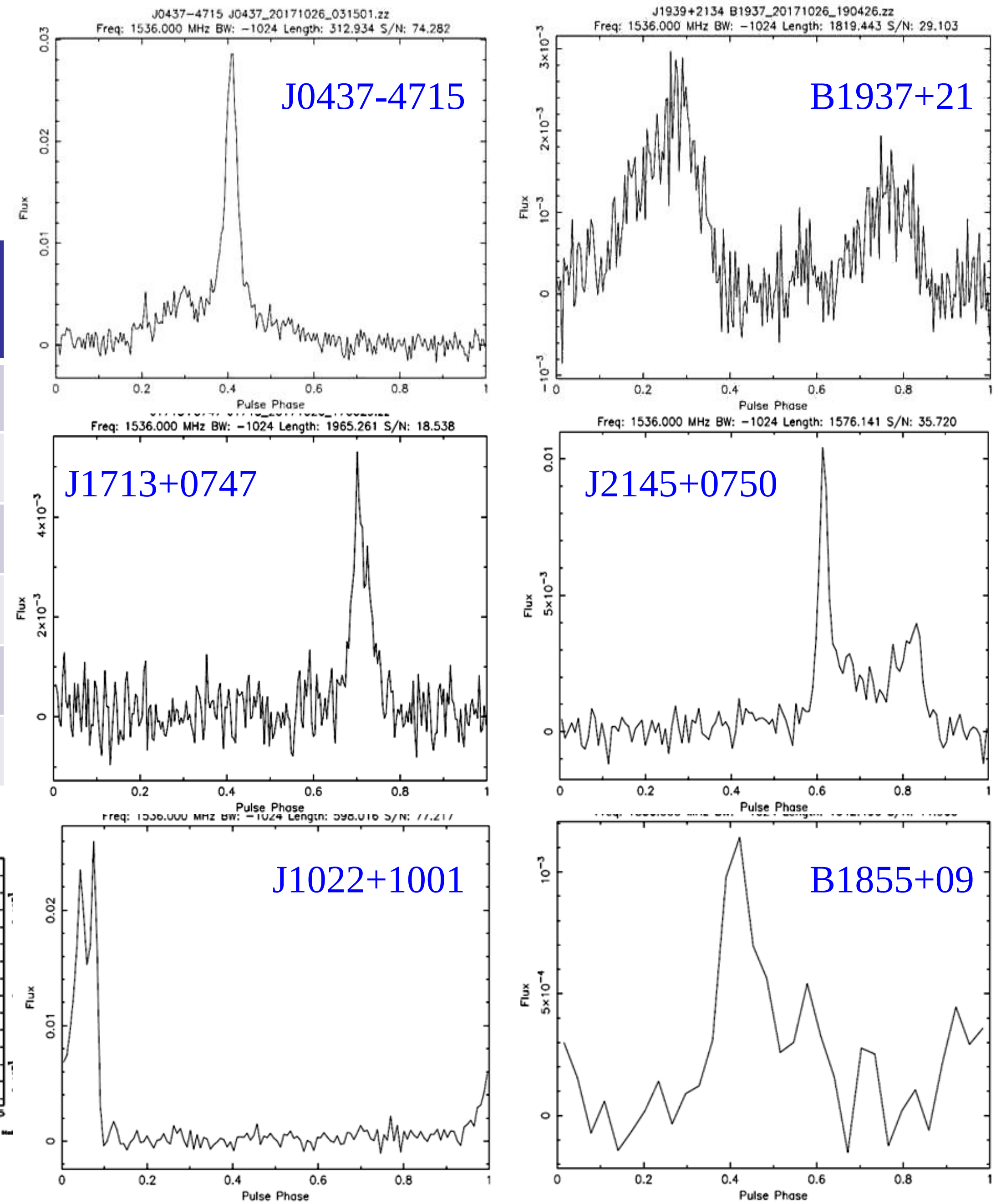


(6) Millisecond pulsars

No	Name	Period (ms)	Flux (mJy)
1	J0437-4715	5.76	149
2	B1937+21	1.56	13.2
3	J1713+0747	4.57	10.2
4	J2145+0750	16.05	8.9
5	J1022+1001	16.45	6.1
6	B1855+09	5.36	5



J0437-4715 Timing residual



(6) Timekeeping at NTSC

- **Maintain local time scale: UTC(NTSC) and UTC(JATC)**

  JATC: Joint Atomic Time Commission in China

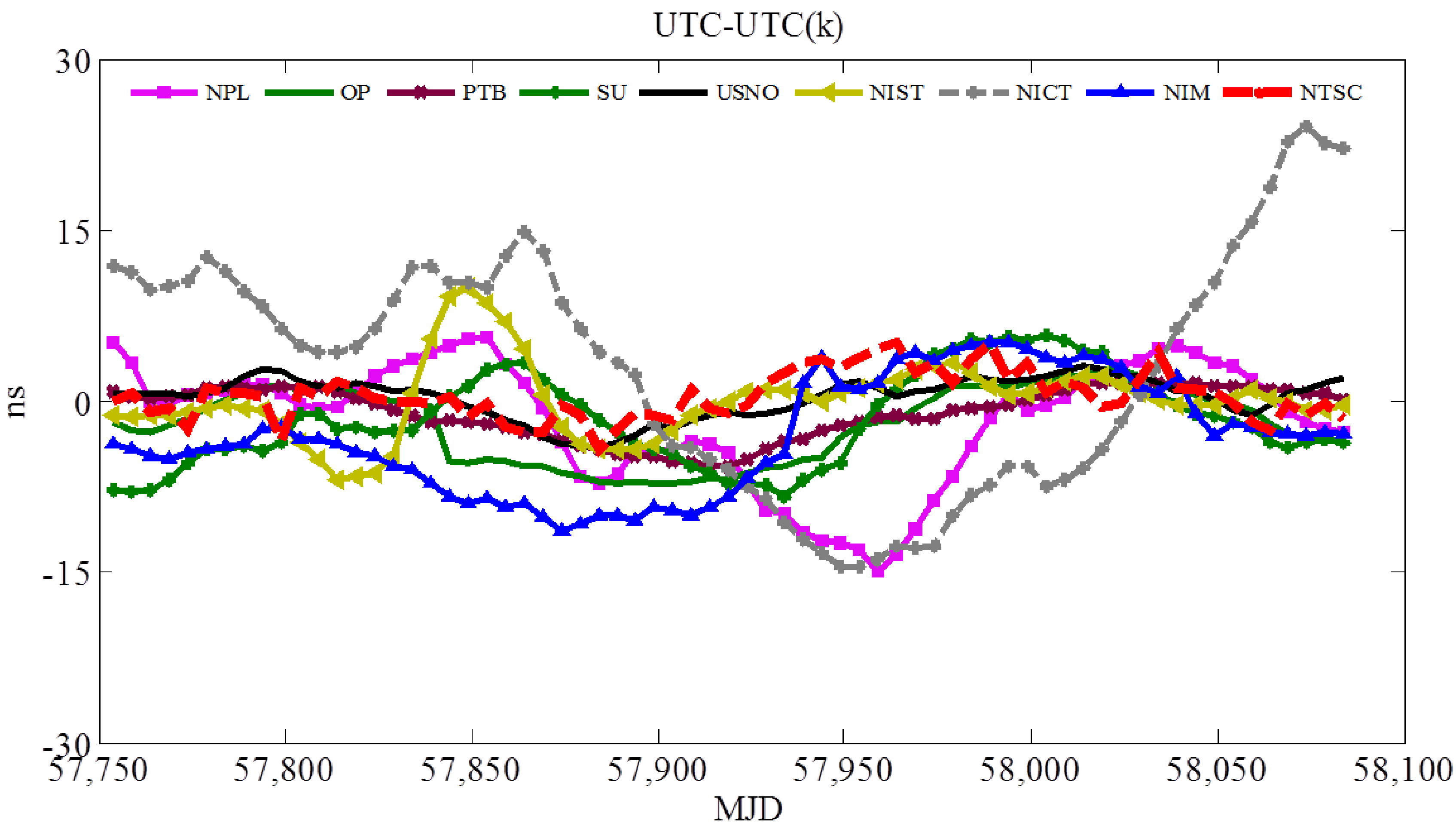
- **Time difference between local UTC(NTSC) and UTC is kept within ±10ns (ITU requirement: |UTC-UTC(K)| <100ns)**

- **UTC(NTSC) is the traceable reference for BPL LF & BPM HF time signal transmission, and BeiDou satellite navigation system.**

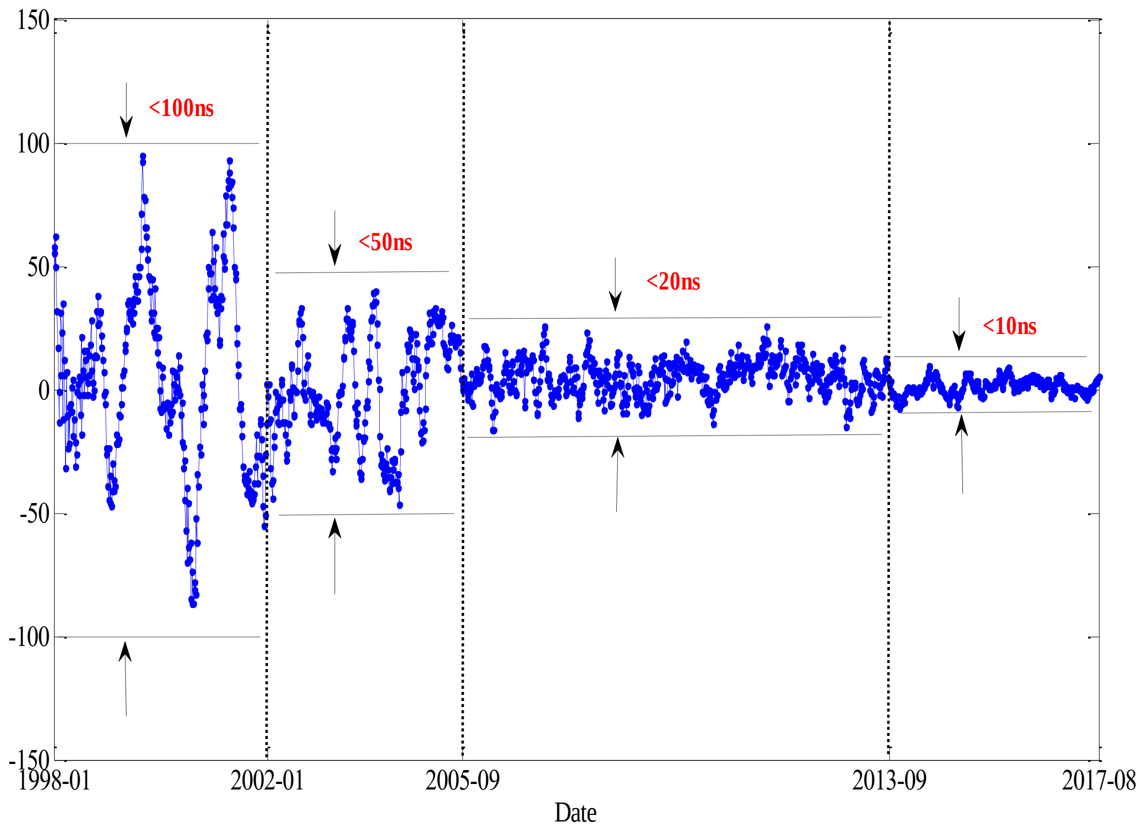
NTSC Timekeeping facilities

Time difference between UTC and UTC(k)

- **China official time reference, UTC(NTSC), at the international advanced level**



UTC(NTSC) control accuracy



Sèvres, 15 October 2016

Dear Dr Shougang Zhang, dear staff members of NTSC,

It is with great pleasure that I address you this message at the occasion of the first 50 years of the National Time Service Centre of the China Academy of Sciences.

My first contacts with your institution were well before I joined the BIPM, when I developed activities also in the field of astronomy, and more particularly, on Earth rotation and reference frames. At that time, it was still the Observatory of the China Academy of Sciences.

After the adoption of atomic time, your institute started the international cooperation in the construction of the international reference time scale, Coordinated Universal Time (UTC). The first publication of *Circular T* at the Bureau International des Poids et Mesures, in 1988, has the contribution of CSAO, located in Shaanxi; this participation had started many years before when the responsibility for time scales was at the Bureau International de l'Heure. NTSC, located in Lintong appeared in the BIPM publications in January 2002. Your institute has worked without interruption to disseminate precise time and has contributed to maintain the international reference UTC.

Please accept my congratulations for the constant progress in your activities. NTSC is today a highly performing institute, with qualified staff operating last-generation clocks and time transfer equipment. This is reflected in the quality achieved by UTC(NTSC), whose divergence with respect to UTC has been kept stable within five nanoseconds most all the time during the last year.

A good collaboration has been established between our respective institutions, both interacting in working groups and through projects common to our scientists. We have been pleased with these interactions, and we wish to continue in the future.

I regret that I am not able to participate personally to this important celebration, but the BIPM and the Time Department are well represented in the ceremony.

All the best,

Dr Elisa Felicitas Arias
Director, BIPM Time Department

UTC(NTSC) accuracy improved with years

From 9.2013, |UTC-UTC(NTSC)|<10ns

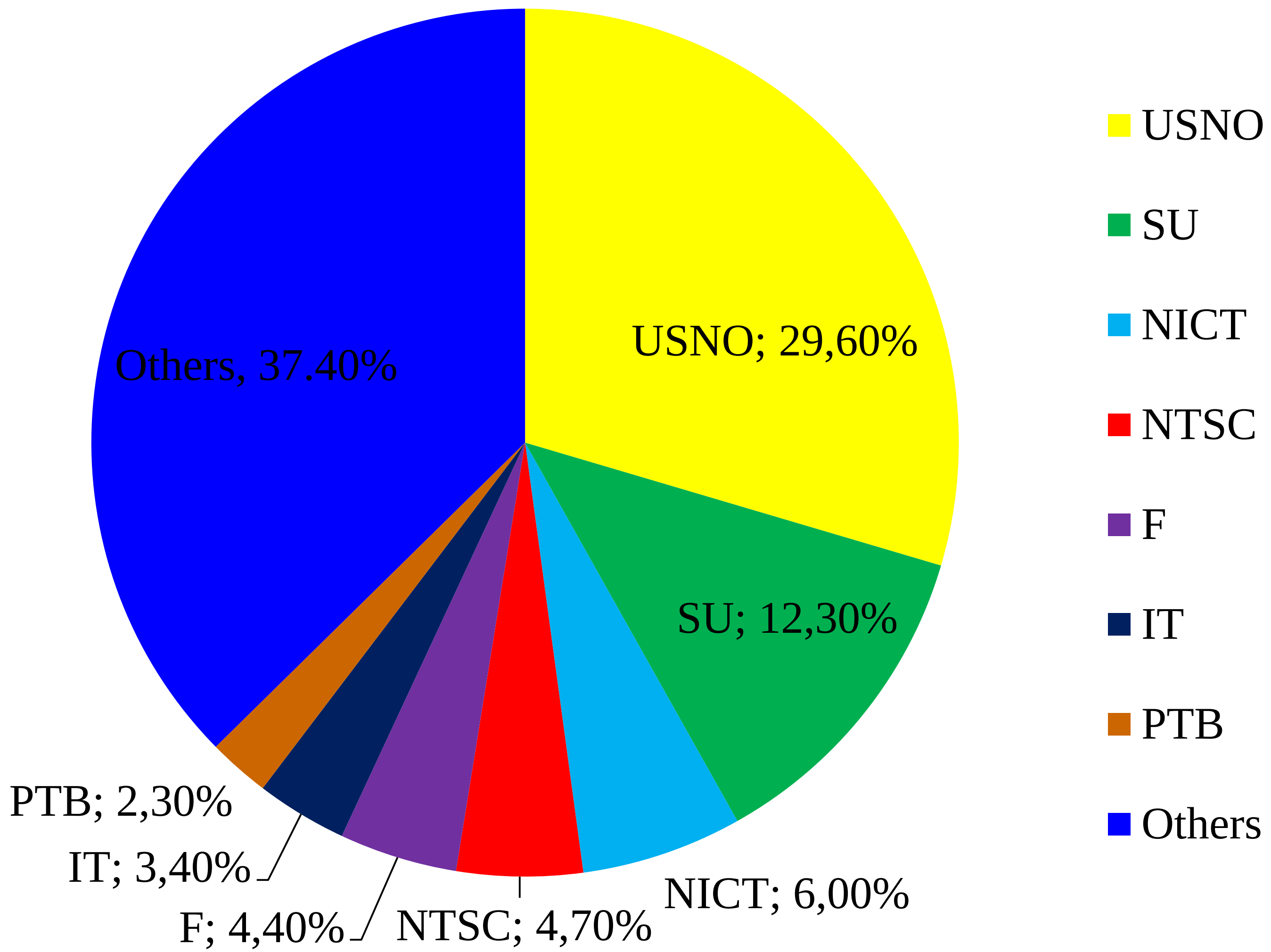
BIPM report

"UTC(NTSC), whose divergence with respect to UTC has been kept stable within five nanoseconds most all the time during the last year"

BIPM time department：Arias

2016.10.15

Contribution to TAI calculation



Time service of NTSC

NTSC has built a high-precision STWTFT and GNSS CV time comparison system with Beidou and be responsible for the time monitoring and evaluation of the Beidou system, and represents the time interoperation of the GNSS system on behalf of the BD.

“**北斗系**统的时间基准为北斗时（BDT）。BDT**采用国**际单位制（SI）**秒**为基本单位连续累计，**不**闰秒，**起始**历元为2006**年**1**月**1**日**协调世界时（UTC）00时00**分**00**秒**，**采用周和周内秒**计数。BDT**通**过UTC（NTSC）**与国**际UTC**建立**联系，BDT**与**UTC**的偏差保持在**100纳秒以内（**模**1**秒**）。”


北斗卫星导航系统
空间信号接口控制文件
公开服务信号（2.1版）

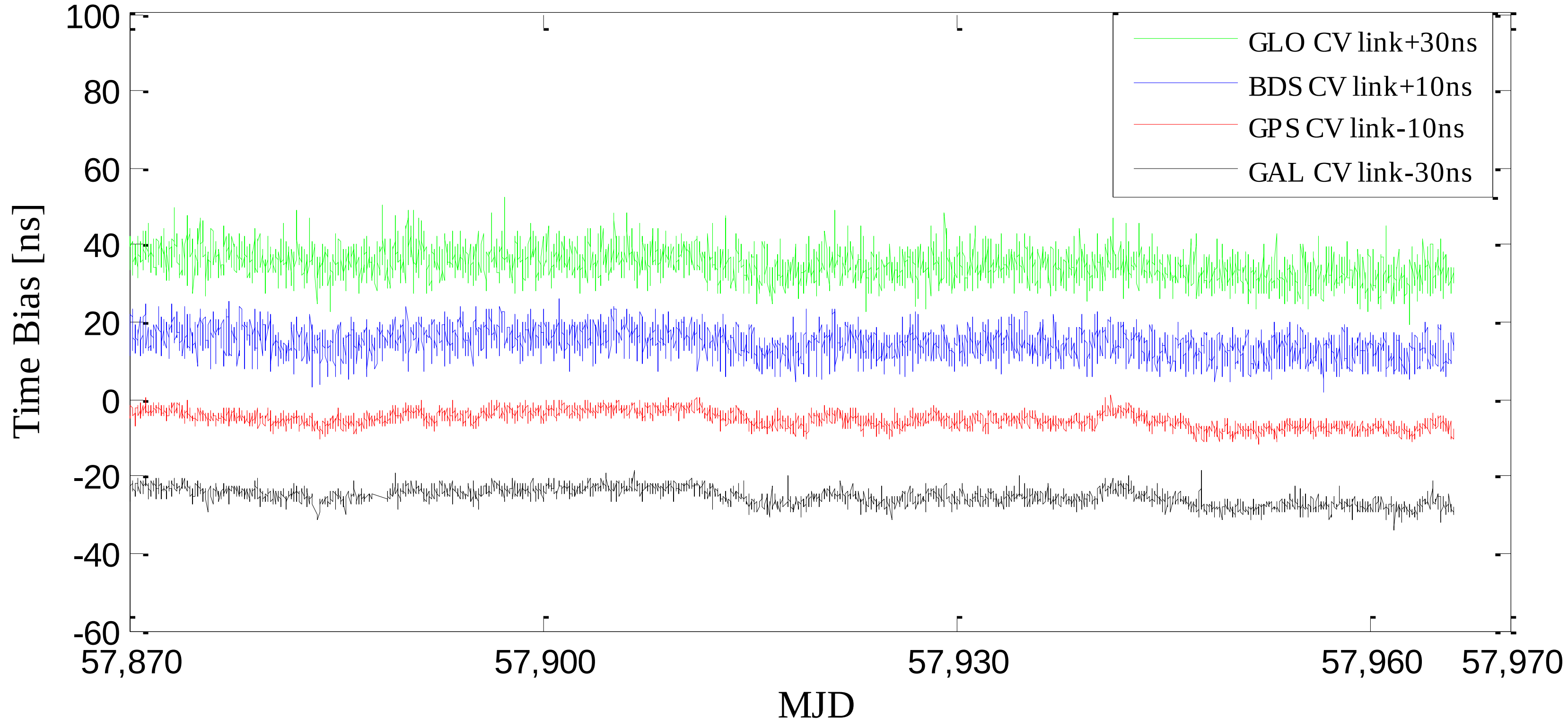
中国卫星导航系统管理办公室
二〇一六年十一月

NTSC provides reliable standard time service, including long-wave，short-wave time system, Beidou system, Navy Changhe 2, GNSS global continuous monitoring system, telephone, network and so on.

《**北斗**卫星导航系统空间信号接口控制文件（2.1**版**）》

(8) BeiDou CV time comparison between NTSC and European UTC(k) laboratories

- **achieved a precision of 2.25ns, same as GPS CV level (currently only 4 BD satellites are visible in Europe)**



Time difference of UTC(SP)-UTC(NTSC) by different links

Metrologia 55(2018) 175-187

(9) NTSC Radio stations

BPL Pucheng

BPM Pucheng

BPC Shangqiu

(10) Chinese Area Position System

CAPS with

4 GEO communication satellite

+

1 IGSO navigation satellite,

results tested in Sep. 2017:

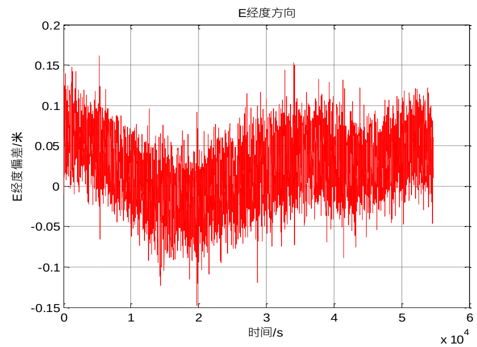
Positioning: 2.0m (PRC ）

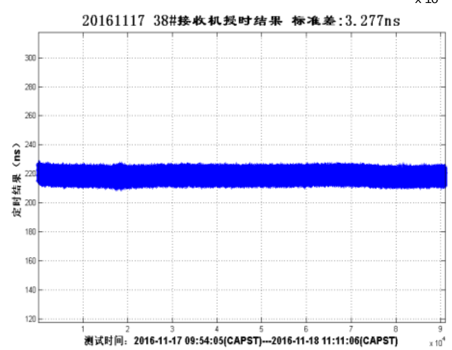
0.5m（CP）

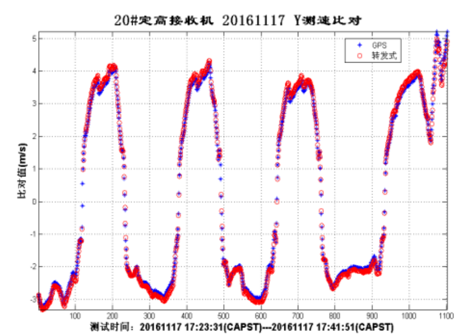
Velocity： 0.2m/s

Timing： 4.0ns（PRC）

3.7ns（CP）







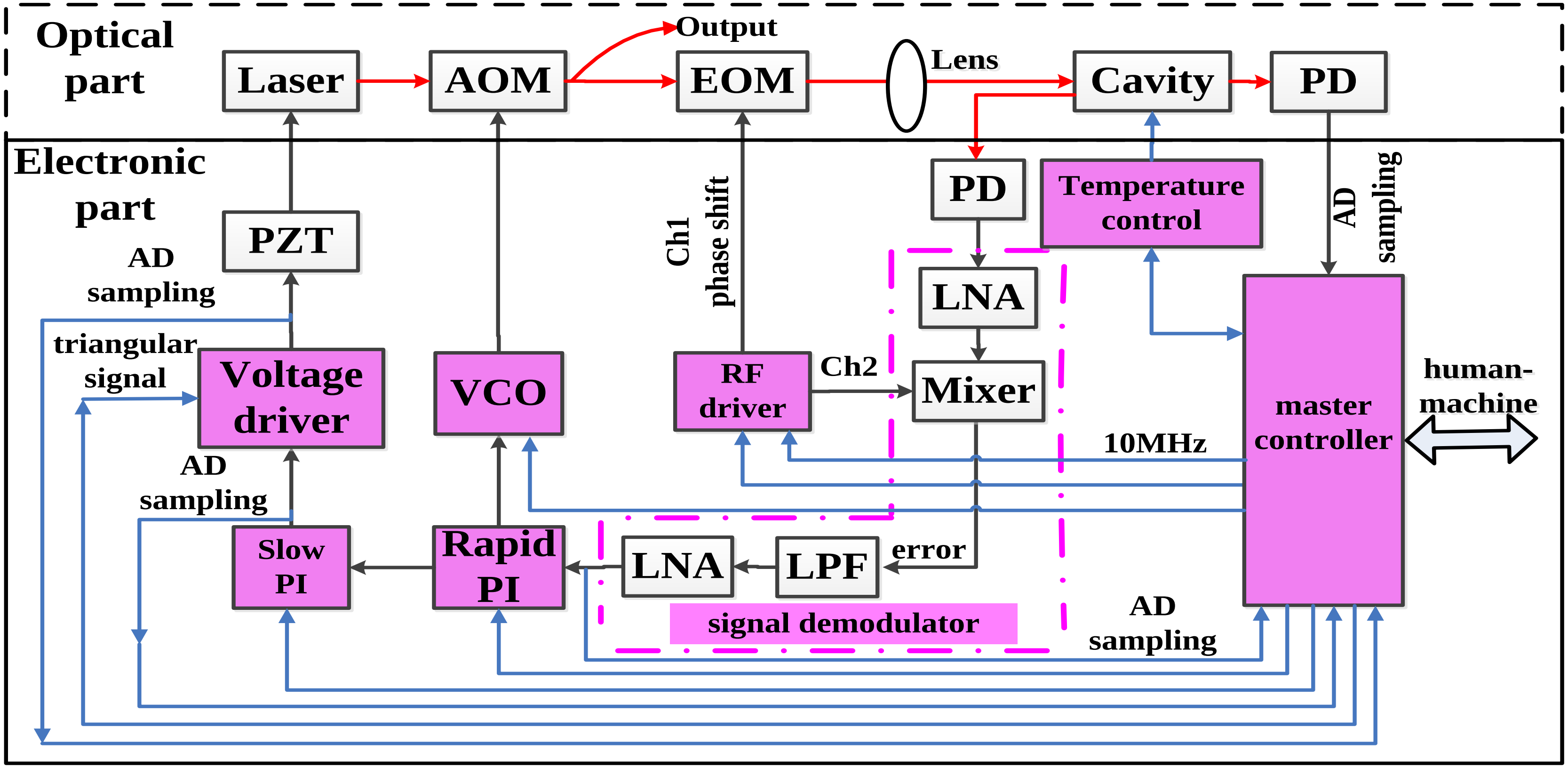
(11) T/F transfer over fiber

Development of auto-run stable laser for fiber transfer

Main function: auto scan/laser frequency lock/relock + ultra-stable

Digital main control + analog proportion integration circuits

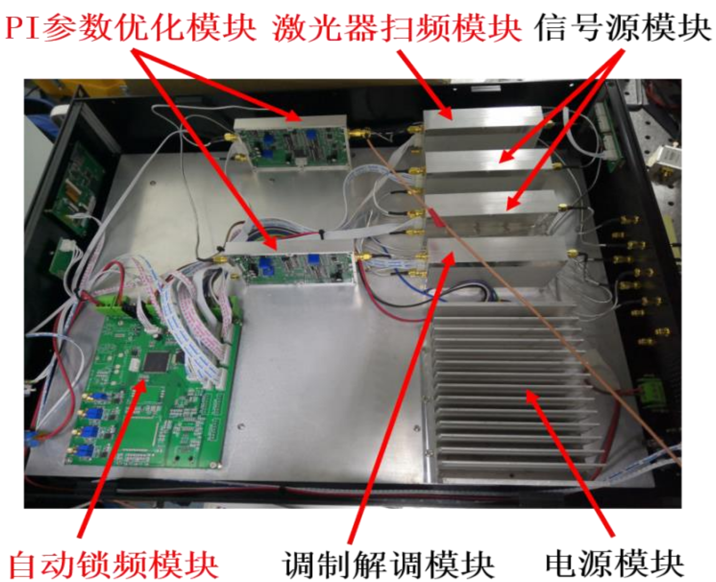
Relock of laser frequency is realized by programmable control process



Digital circuits: SMART function(auto lock, continous operation)

Analog circuits: laser frequency stability

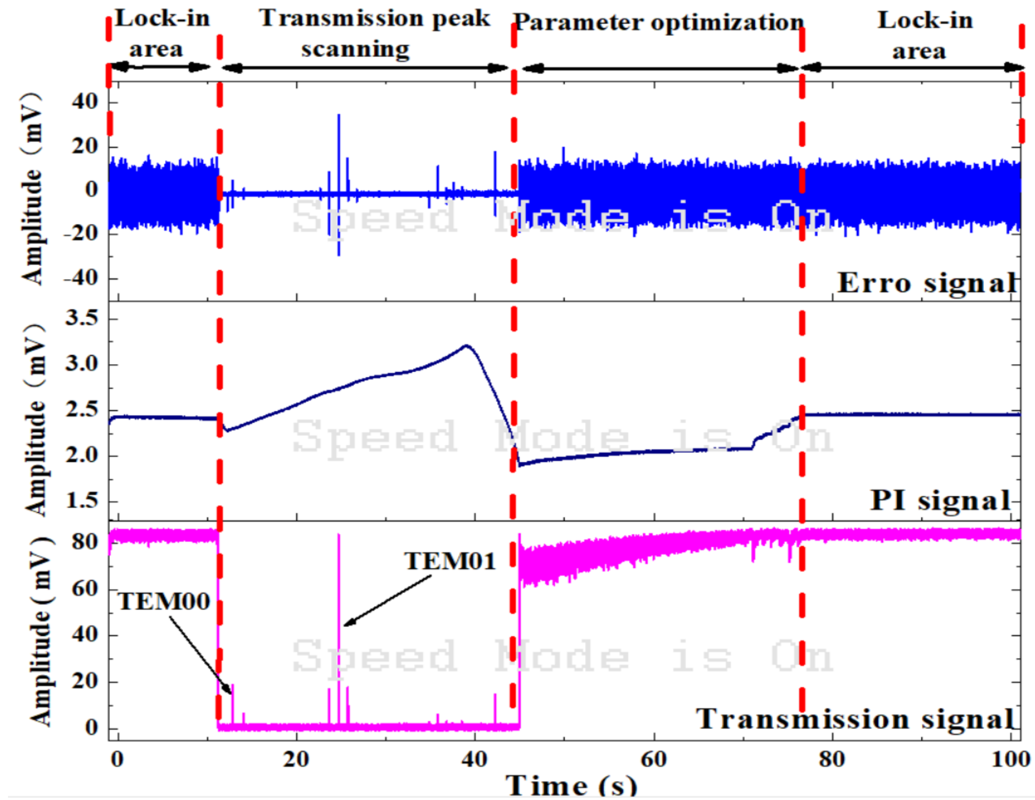
Development of auto-run stable laser for fiber transfer



relock circuits

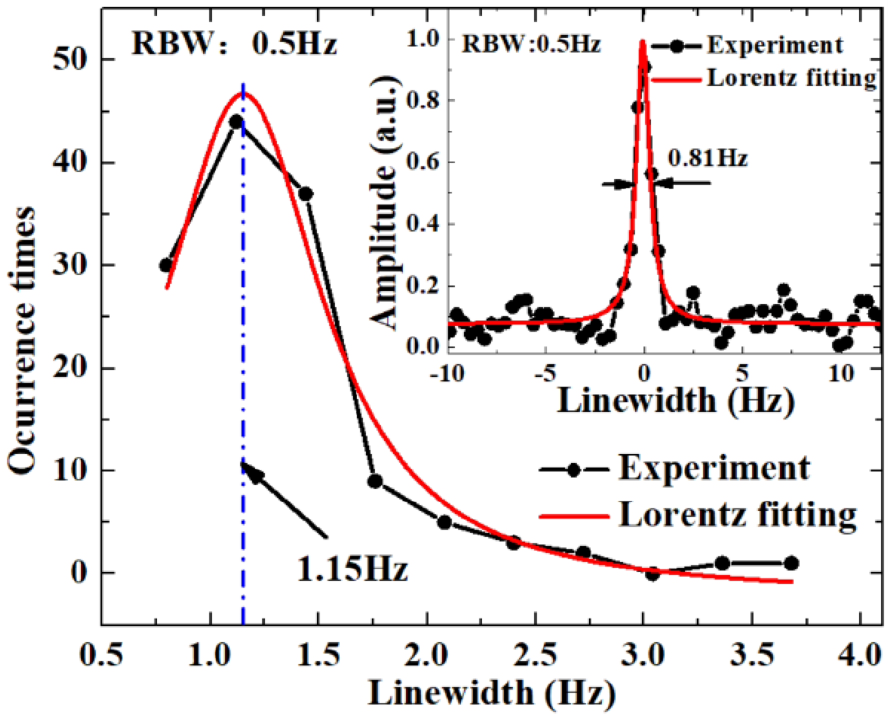
User interface

A typical relock process

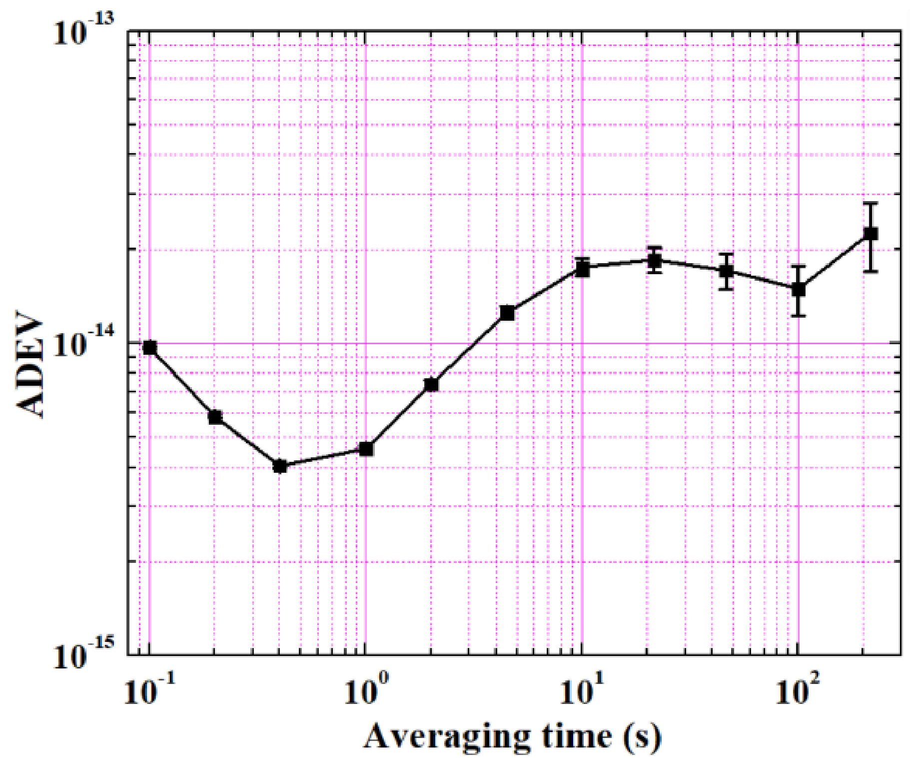


- scan-time: 33s， optimization: 32s
- Size：2U
- relock cycle time can be reduced to <30s

Development of auto-run stable laser for fiber transfer

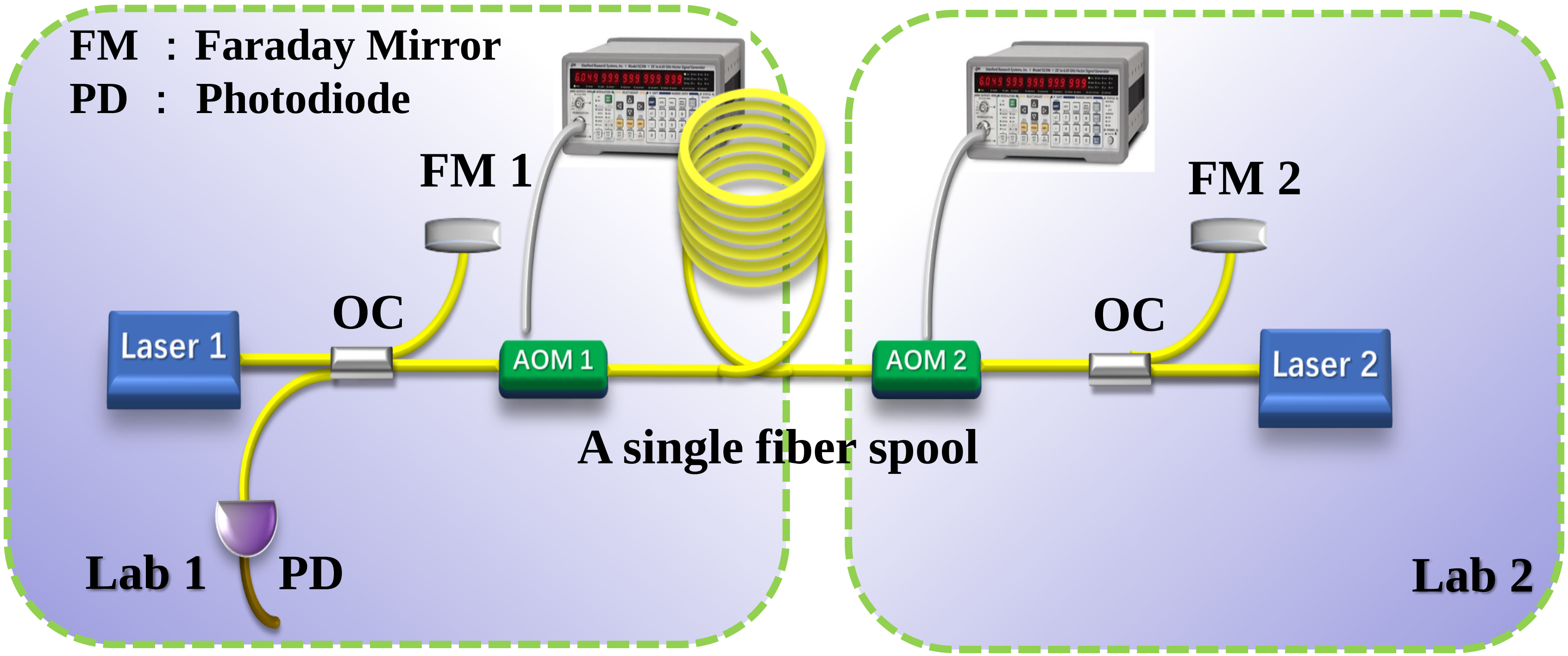


laser linewidth



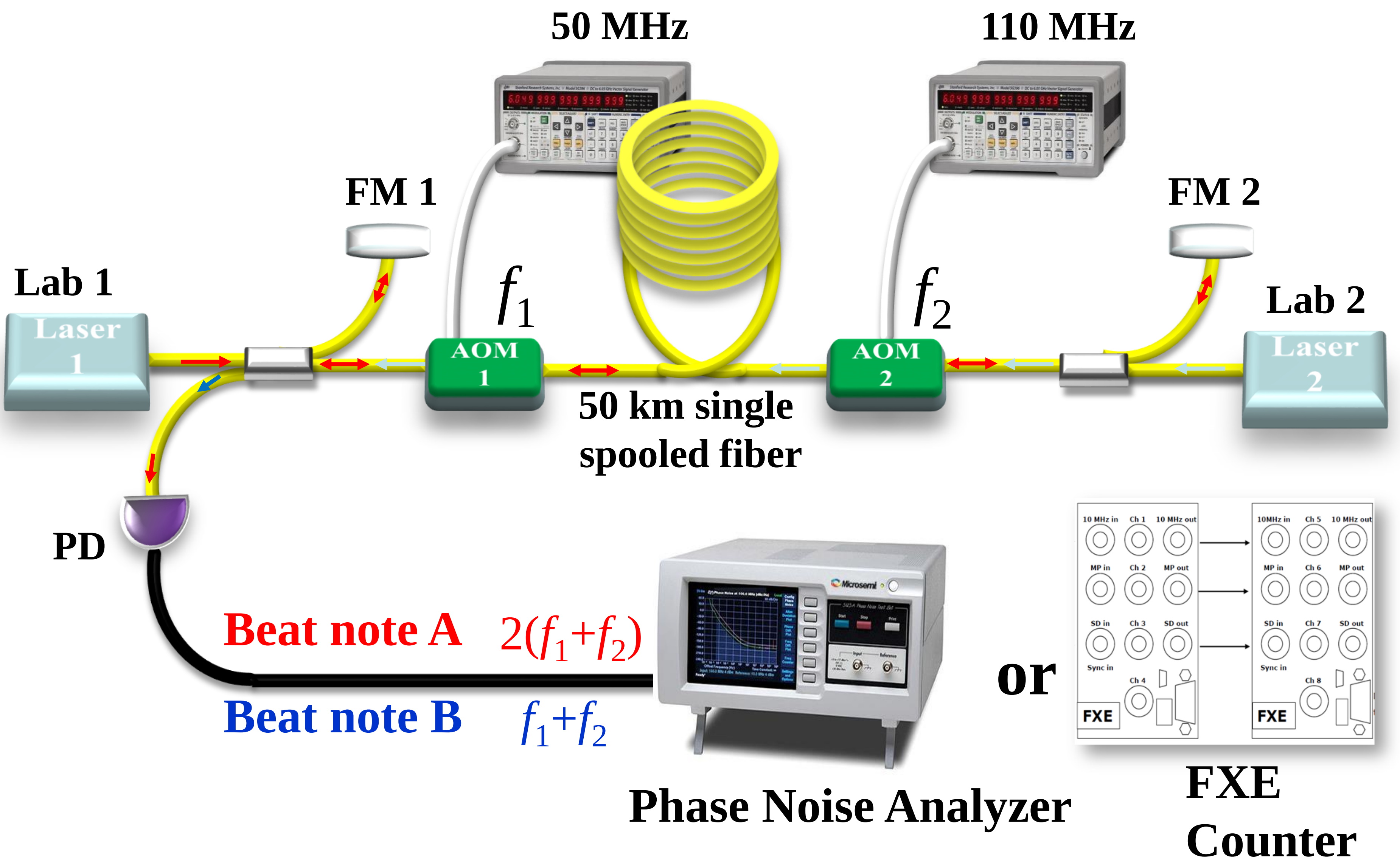
- laser linewidth$_{mp}$: 1.15Hz
- laser linewidth$_{min}$: 0.81Hz
- frequency stability 4.3e-15@1s

Optical phase comparison by local measurement

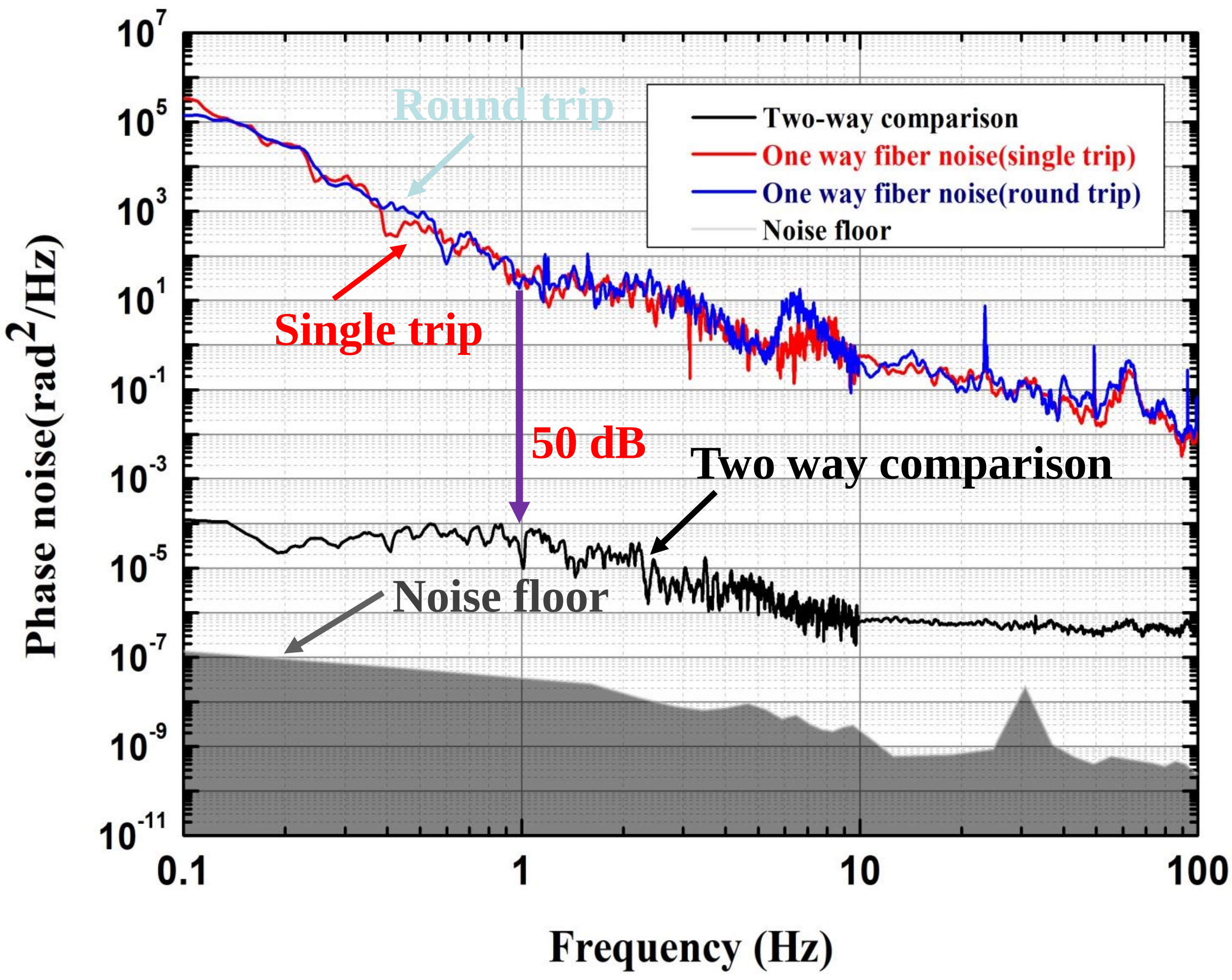


- **One bidirectional fiber link for laser transferring to avoid the phase noise difference between two fiber links**
- **Direct phase comparison without active noise control**
- **Local measurement without data transfer in distant labs**

The Experimental setup



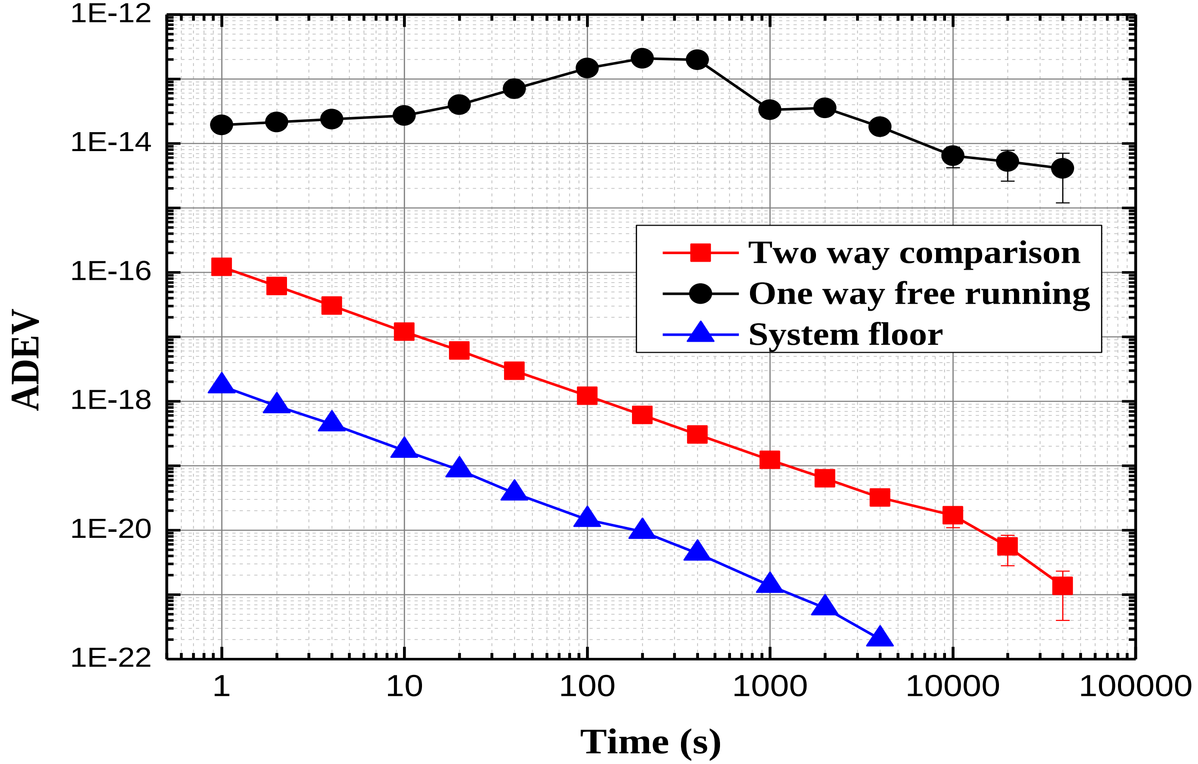
Results and discussion



- About 5 magnitudes below one-way fiber noise at 1 Hz
- The phase noise can be rejected using the two-way setup

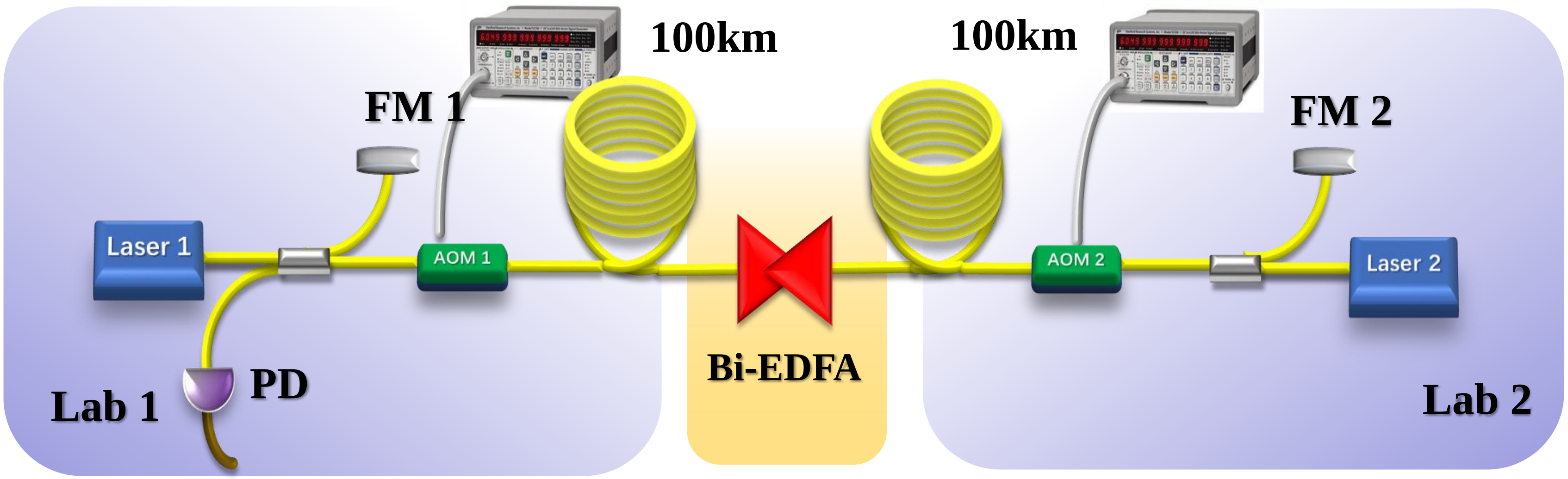
Results and discussion

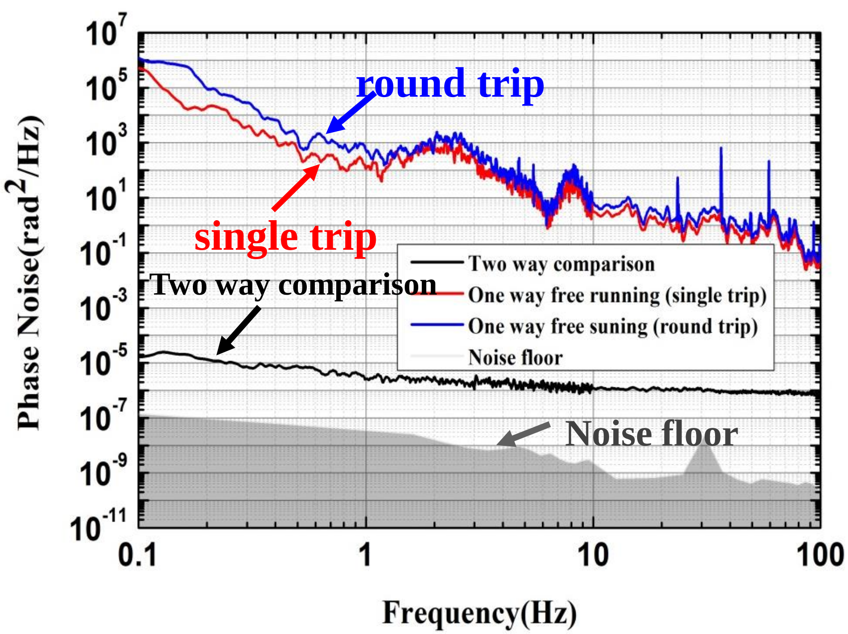
The precision of frequency comparison

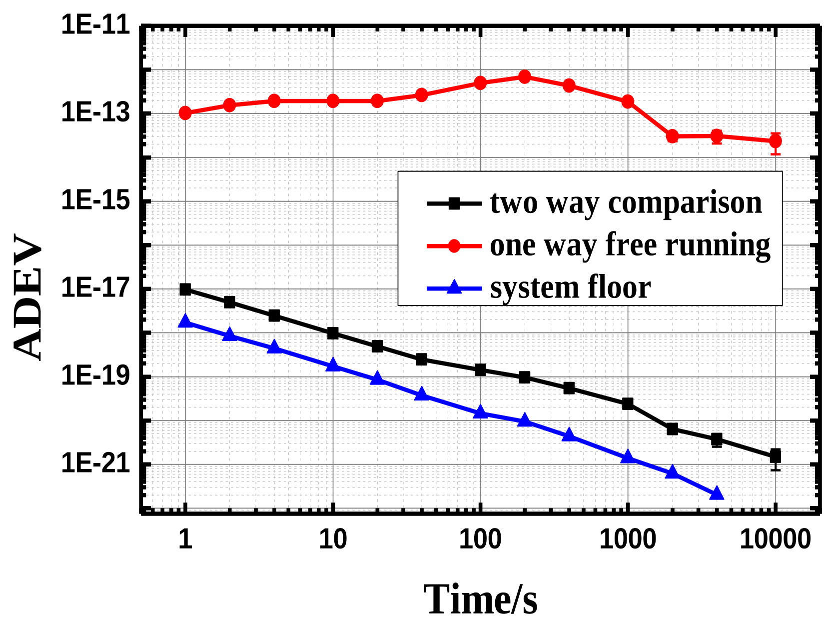


- **1.2E-16 at 1 s , 1.3E-21 at 40,000 s , Scales down as 1/*τ***
- **Long-term stability is improved by more than 6 orders**

Extension of distance to 200km

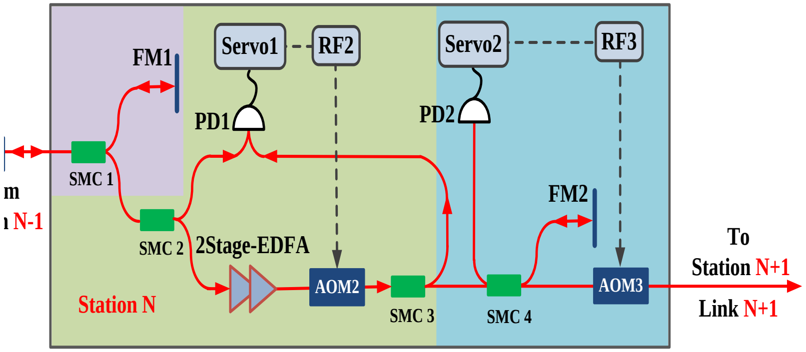


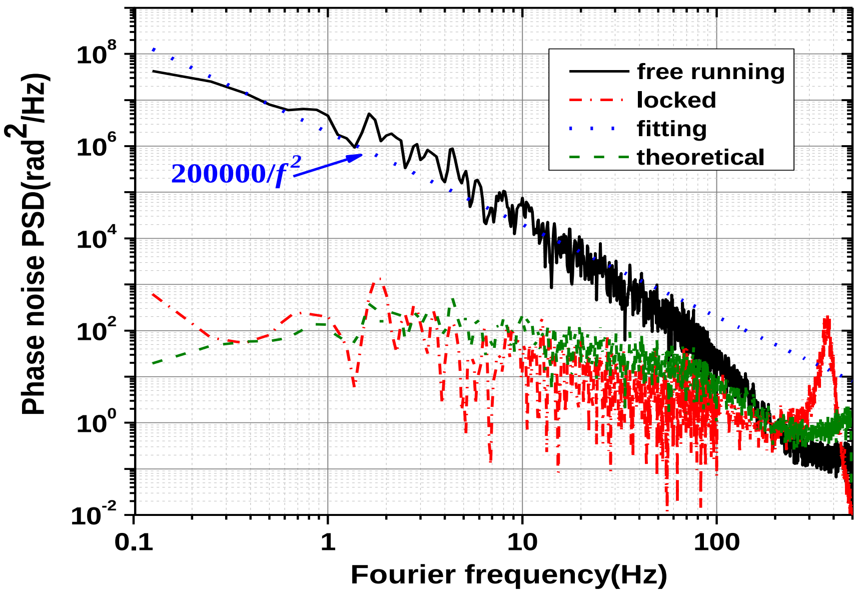


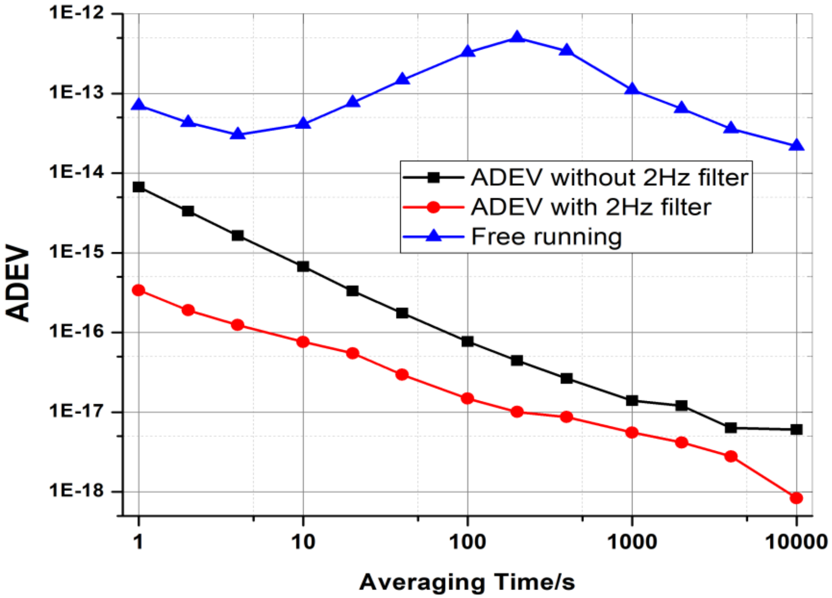


Optical Frequency Transfer over Fiber

- New cascaded frequency transfer scheme based on unidirectional EDFA with a lower extra phase noise and a less sensitivity to back scatter light
- Cascaded 112km+112km field fiber link with a transfer instability
- free-run: 7E-14/s;
- after lock:<4E-16/s, 8E-19/10000s

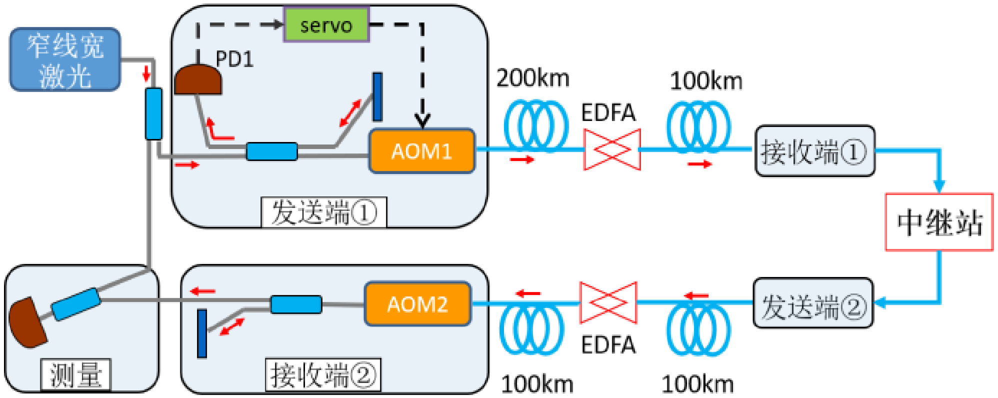




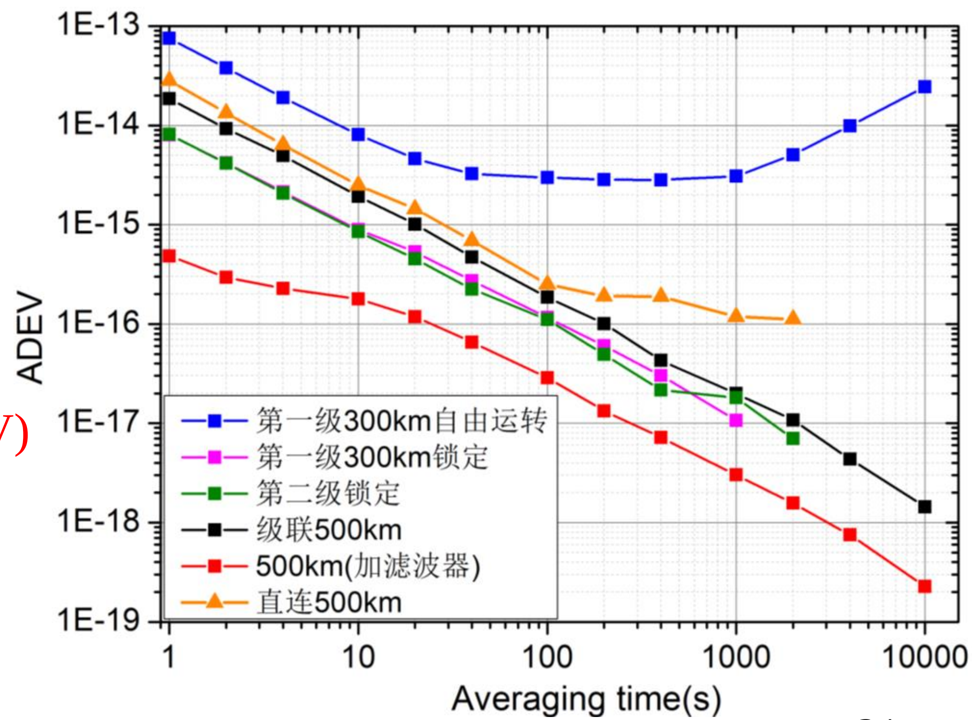


Optical Frequency Transfer over Fiber

- (300+200) 500km cascaded lab fiber link
- Combination of optical PLL and EDFA

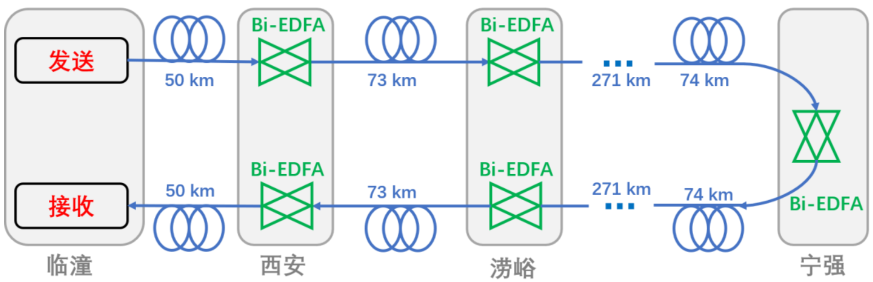


- 2 EDFA applied in the 1st 300km
- 1 EDFA applied in the 2nd 200km
- cascaded link improve the noise compensation by shorten signal delay
- Stability(500km): 2E-19/10ks (mod-ADEV)
- Counter: Lamda mode

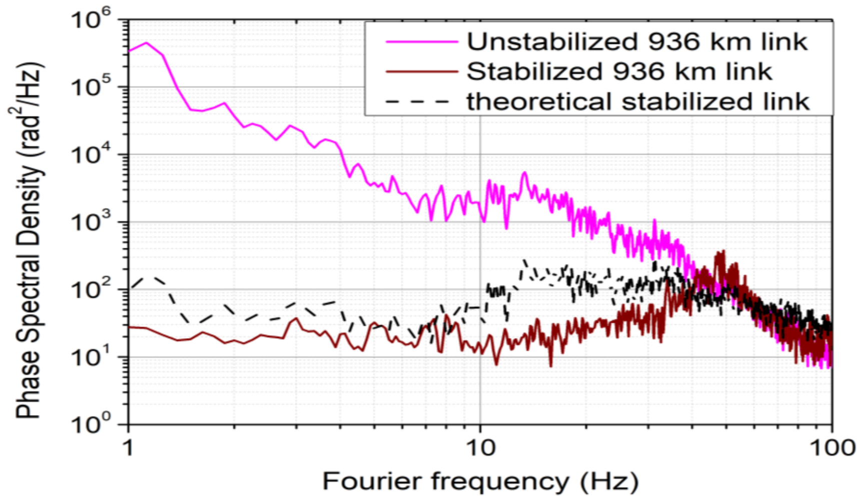


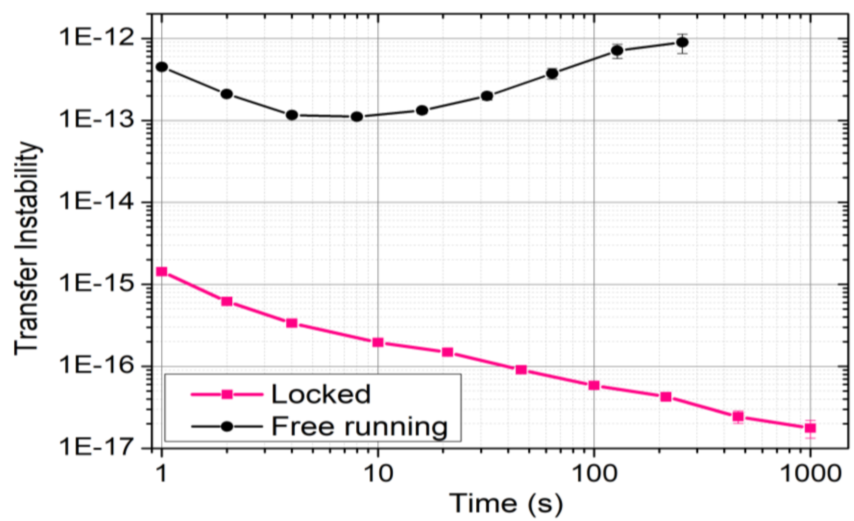
Optical Frequency Transfer via 936km Fiber

- Lintong-Ningqiang round-trip 936km
- telecomm fiber buried along highway
- Total loss=248dB,13 EDFA
- Fiber type: G652+G655
- Counter: Lamda mode



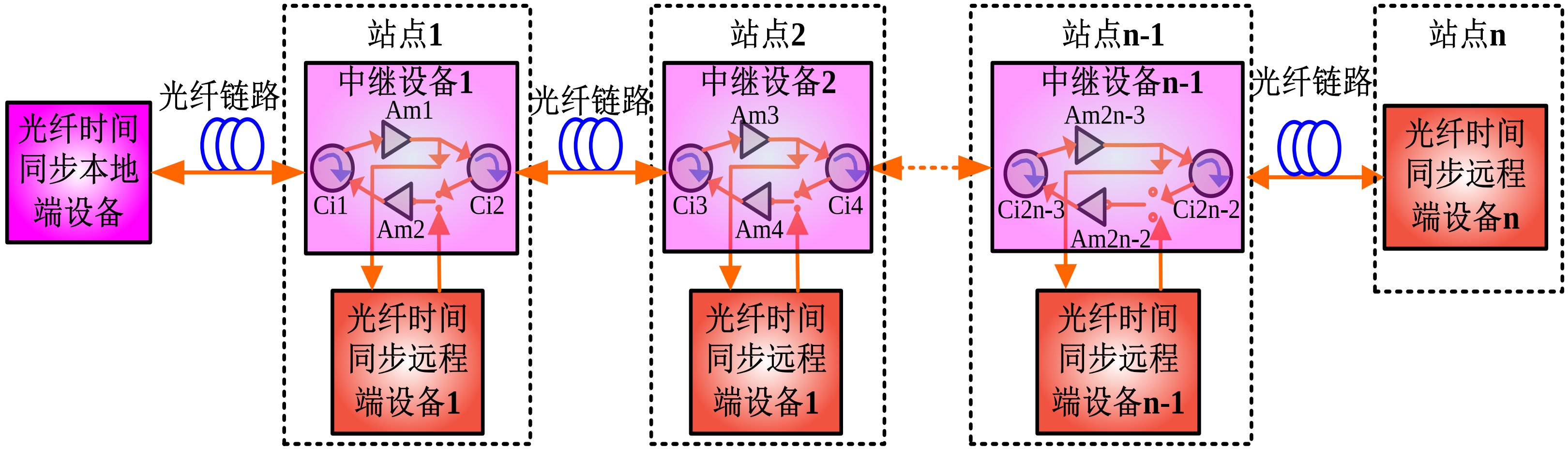
Phase noise of the link@1Hz reduced by 65dB
Control bandwidth 48Hz limited by time delay





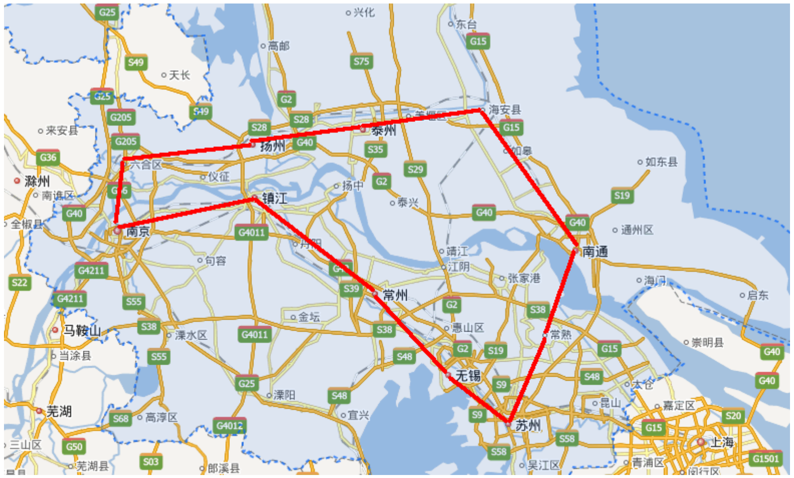
free-run stability:5E-13/s
stabilization: 1E-15/s, 1E-17@1000s (Mod-ADEV)

Multi-user Time transfer via telecom fiber



- Signal: 1PPS, IRIG-B time code and 10MHz frequency
- Single DWDM channel
- Each end-node is schronizied after a cycle of two-way comparison by the local site consequently
- Multiple end users based on remote compensation scheme
- Time division multiple access, TDMA
- Compatible with various topological network

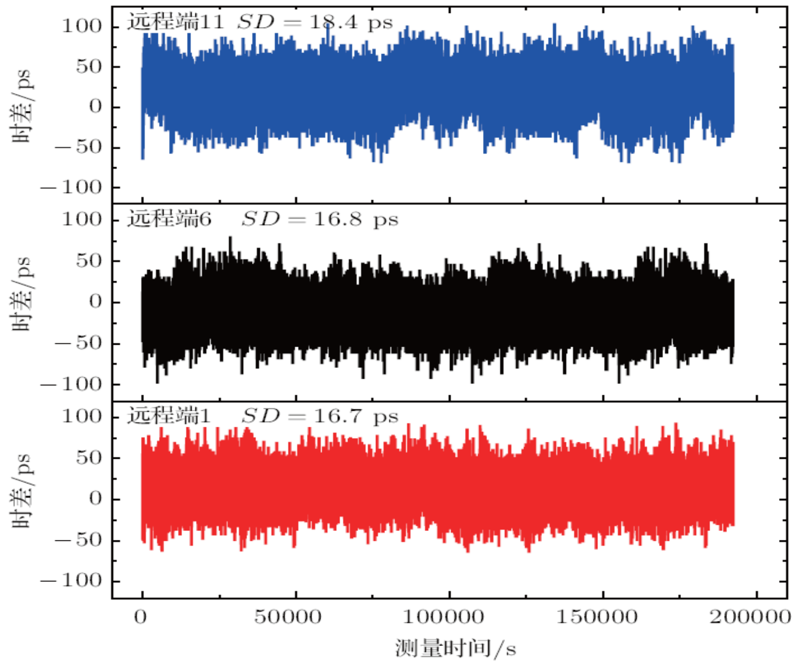
Time transfer via 871km telecomm fiber

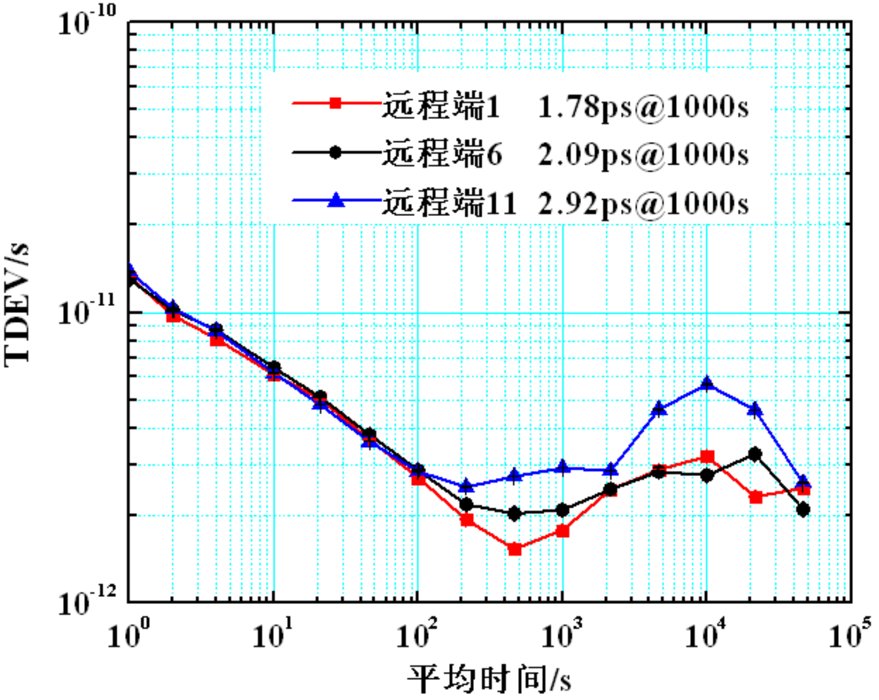


编号	站点名称	站点距离（km）	衰减 (db)	传输时延及变化 (ps)
1	南京	0	0	0
2	镇江	102	23	506892384±12672
3	常州	97	23	950342656±21382
4	无锡	59	14	1309193728±23911
5	苏州	71	17.5	1660607616±33212
6	常熟	68	15.5	1992951424±34451
7	南通	93.4	21	2451252258±43635
8	海安	89	19.5	2887329663±45178
9	泰州	69	17.5	3228732983±53682
10	扬州	72	18	3581541839±55037
11	六合	68	15.5	3905313243±56369
12	南京	83.2	18.5	4303540527±66423
	全程	**871.6**	**203**	**4303540527±66423**

871km field fiber, G652, all-solded fiber,10 repeater stations

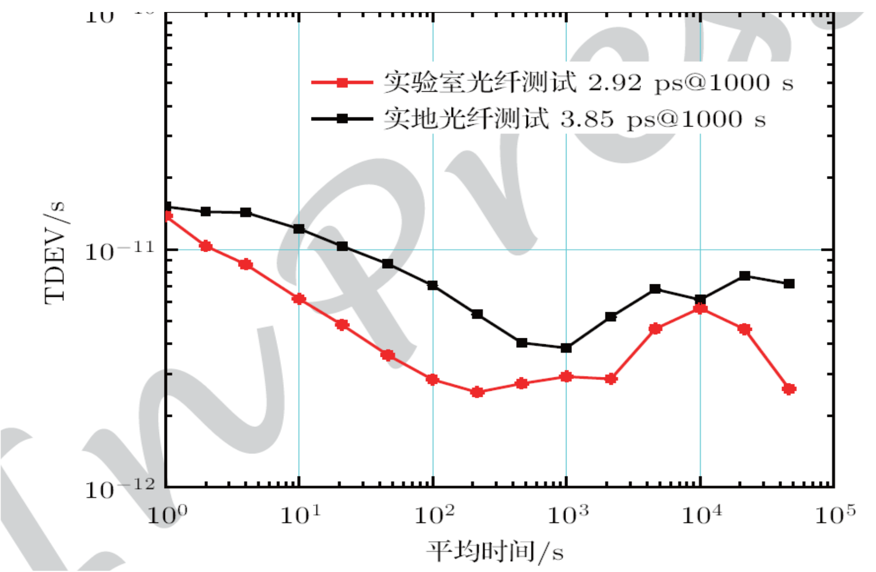
Time transfer via 871km telecomm fiber





Tests on lab fiber spools:

- Timing jitter SD of remote stations (1,6,11) <20ps
- TDEV of remote stations (1,6,11)<3ps@1000s
- Residual time variation related to temperature



Test on the telecomm fiber:

- TDEV of remote stations (871km)<4ps@1000s

Time transfer via 871km optical fiber

	Uncertainty (ps)	
	550km fiber coil	871km field fiber
thermal drift	6	12
TDC	21	21
wavelength	1.9	6
repeater	4	5
TOTAL	22.5	25.4

	Instability SD(ps)	
	550km fiber coil	871km field fiber
thernal drift @electronics	5	10
cotrol delay	2	2
TDC resolution	8	8
calibration	8	8
residual fiber	13.6	25.6
TOTAL	18.5	29.8

Time transfer via 1085km optical fiber

1085km telecomm fiber along highway

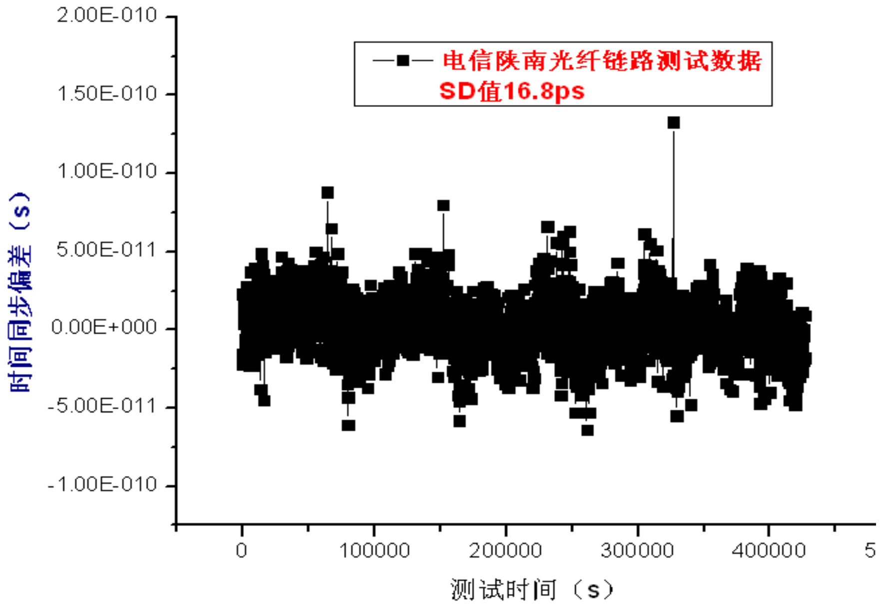
1 to 16 end-uses time transfer

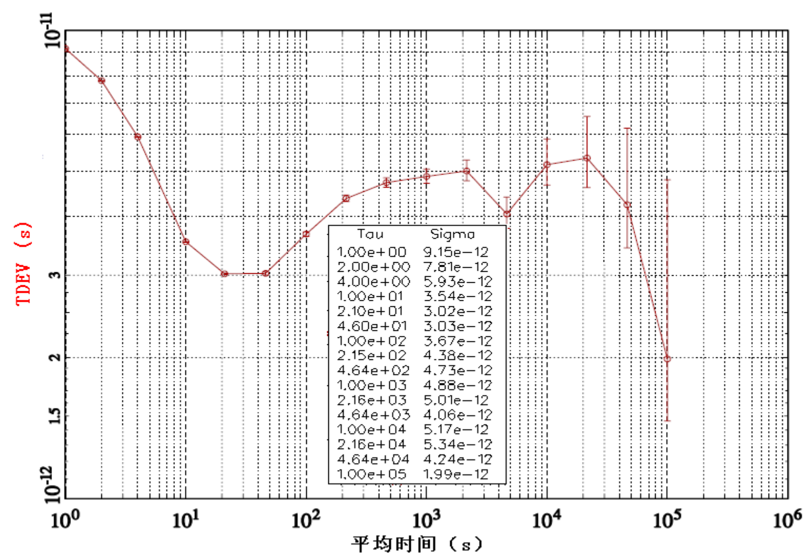
Fiber type:G655+G652

2 SFP@2 DWDM: SNR 10→30dB

TDC →home-made Time-Voltage Conv.

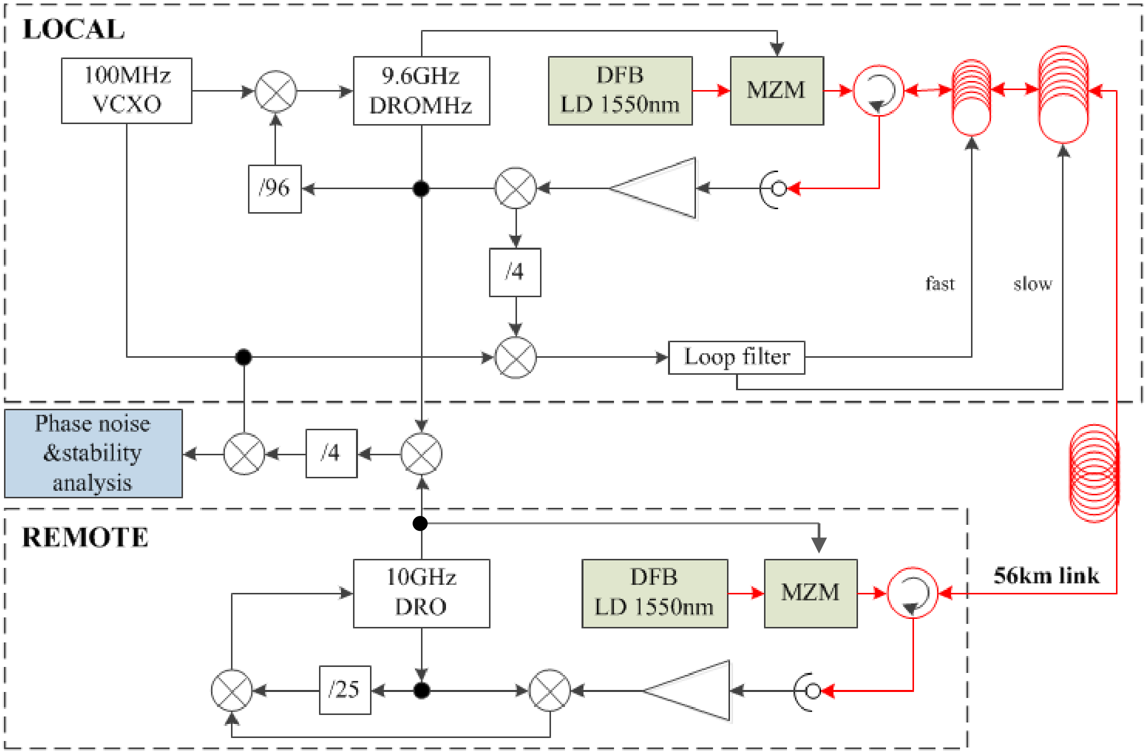
resolution:20ps/s→3ps/s

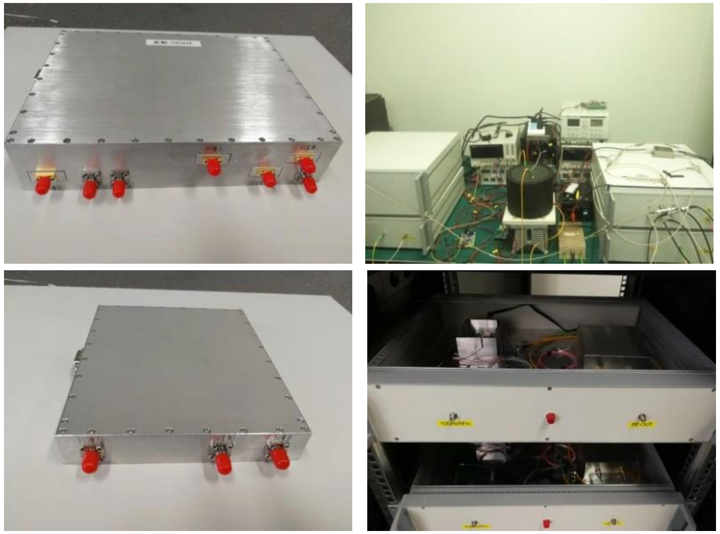


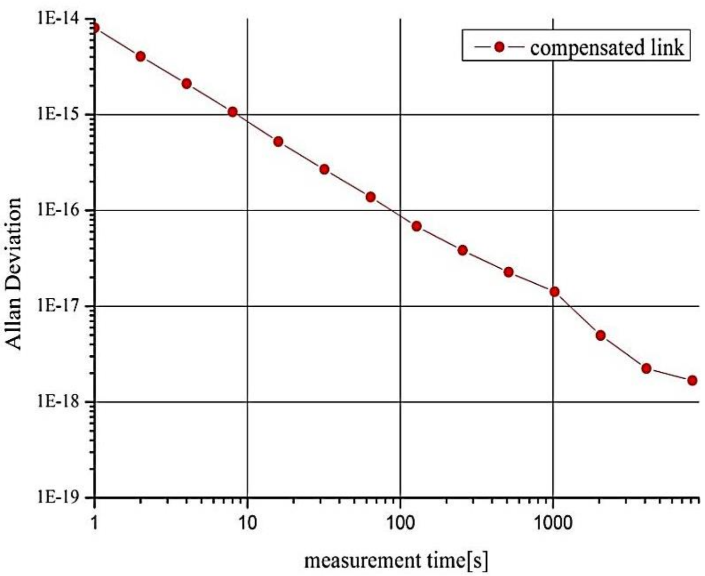


time jitter SD: 16.8ps, TDEV:5ps@1000s

Microwave Frequency Dissemination on 56-km Fiber Spool







By analyzing the phase variation between the local end 9.6 GHz and the remote end 10 GHz, we obtain a frequency instability of the link of 8.06E-15/s, 1.67E-18/8200s.

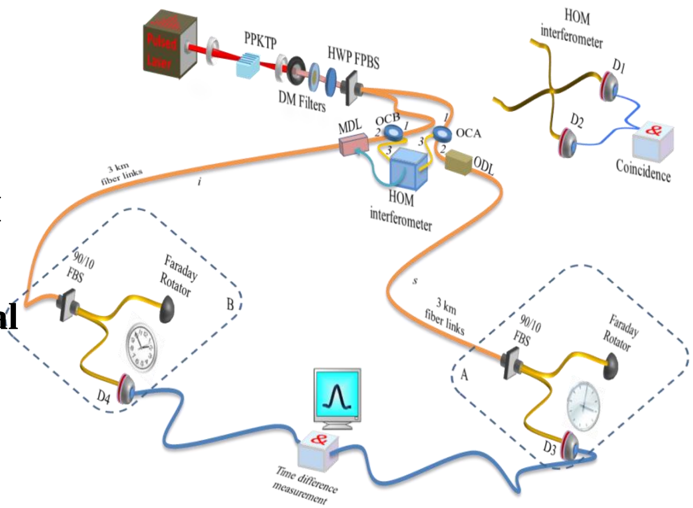
Quantum Clock Synchronization based on Second-Order Coherence over 6 km fiber link

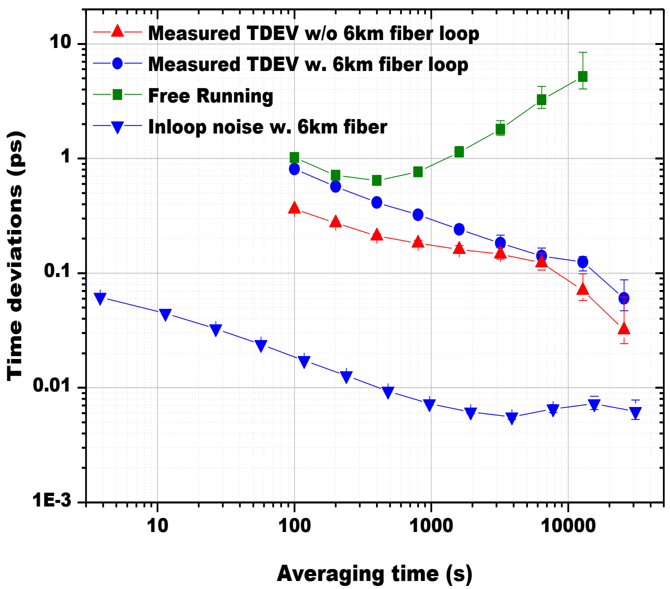
Source: 1582nm frequency-correlated photon pairs

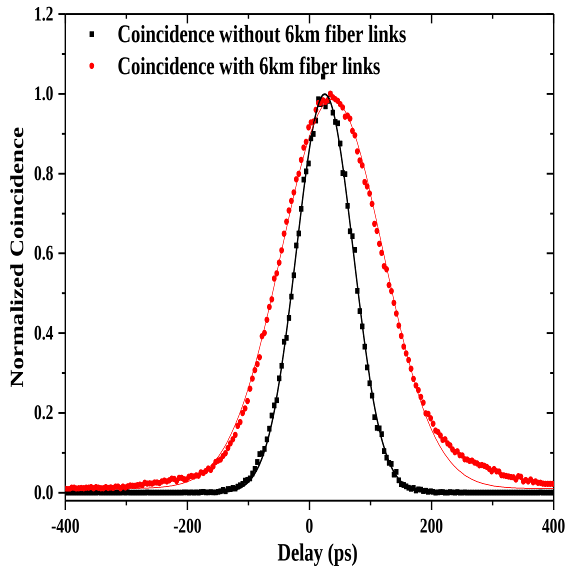
Transmission path: two 3km-long fiber coil

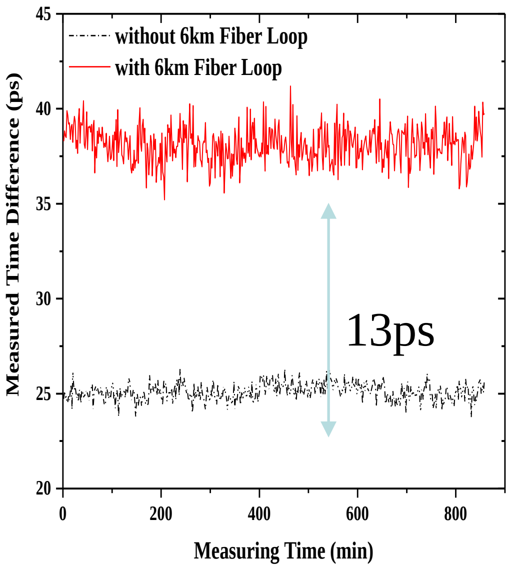
Second-order coherence: HOM interference

Coincidence measurement: local coincidence hardware, Picoharp 300



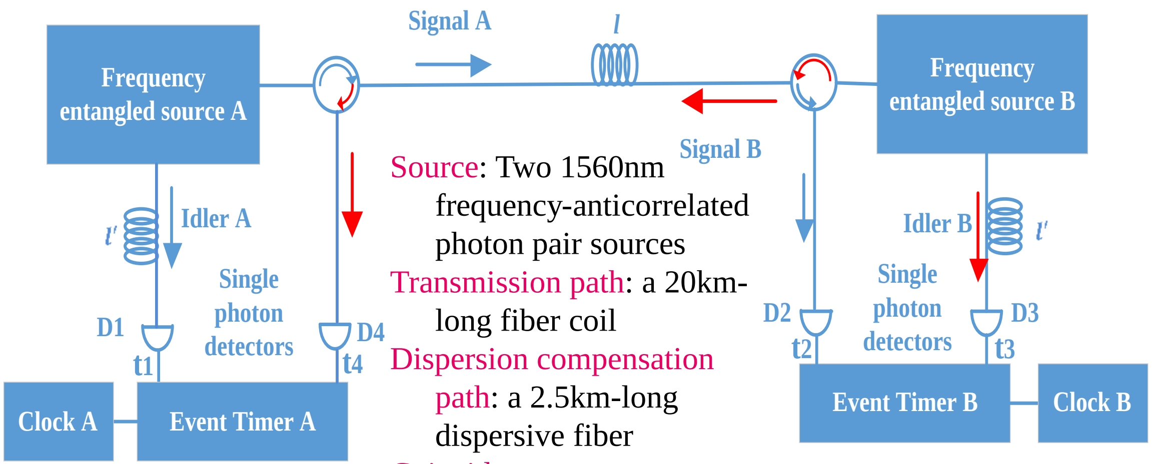






- **Minimum TDEV: 60 fs@25600 s**
- **Ultimately limited by the in-loop jitter: 6 fs@3900 s**
- **Accuracy: 13ps**

Two-way Quantum Clock compare over 20 km fiber link



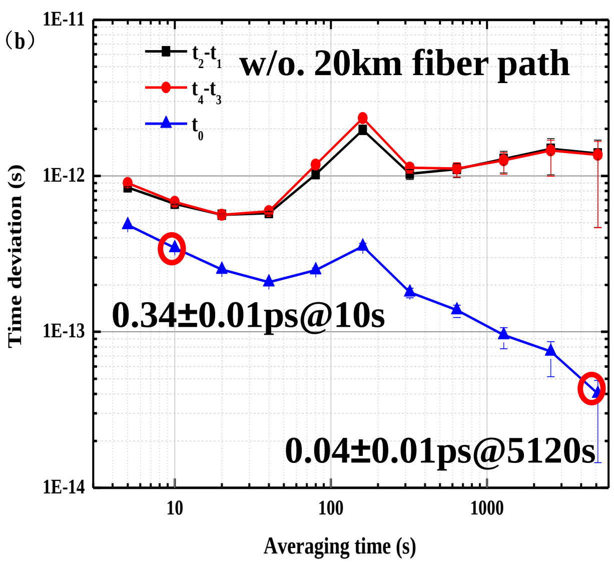
Source: Two 1560nm frequency-anticorrelated photon pair sources

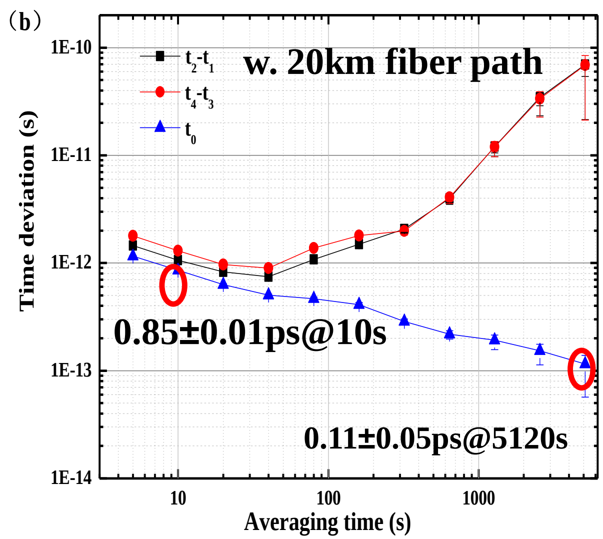
Transmission path: a 20km-long fiber coil

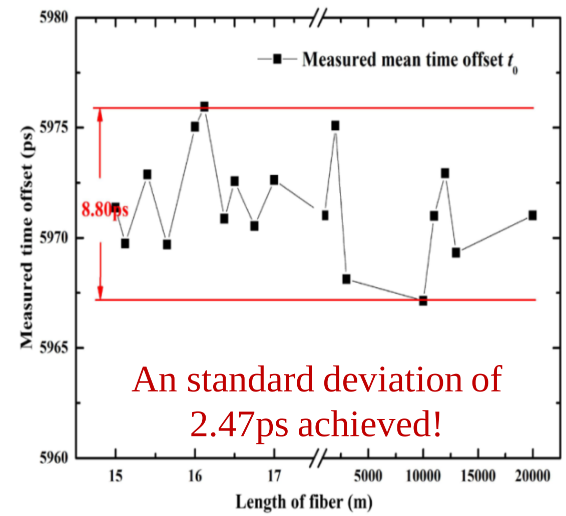
Dispersion compensation path: a 2.5km-long dispersive fiber

Coincidence measurement: Nonlocal, ET033-A Event timers

- **Minimum TDEV: 110 fs@5120 s**
- **Ultimately limited by the systematic jitter: 40 fs@5120 s**
- **Accuracy: 2.47ps**







An standard deviation of 2.47ps achieved!

Important projects for NTSC

- Establishment of precision land-based time service system: new LF radio and optical fiber time service infrastructure.

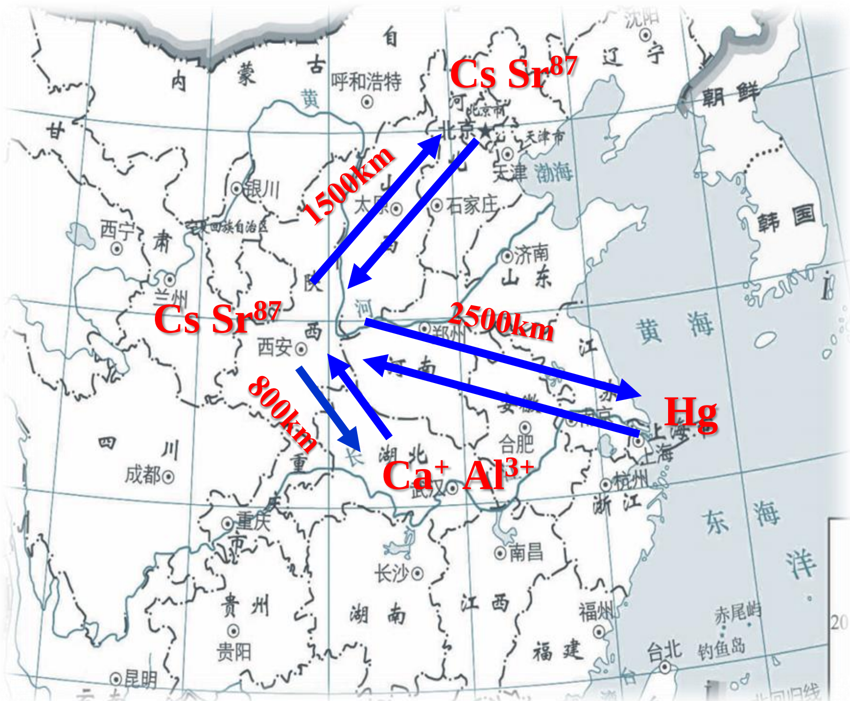
- Precision Time-Frequency experimental system in Chinese Space Station

Precision land-based time service system

Projected completion in 2023

The part of T/F service via fiber ：

Using the telecom fiber to connect Beijing, Xi'an, Shanghai, Wuhan, Hefei, Urumqi, Sanya and other important cities and important users, more than 20000km optical fiber time service backbone network



Atomic clocks or optical clocks in China

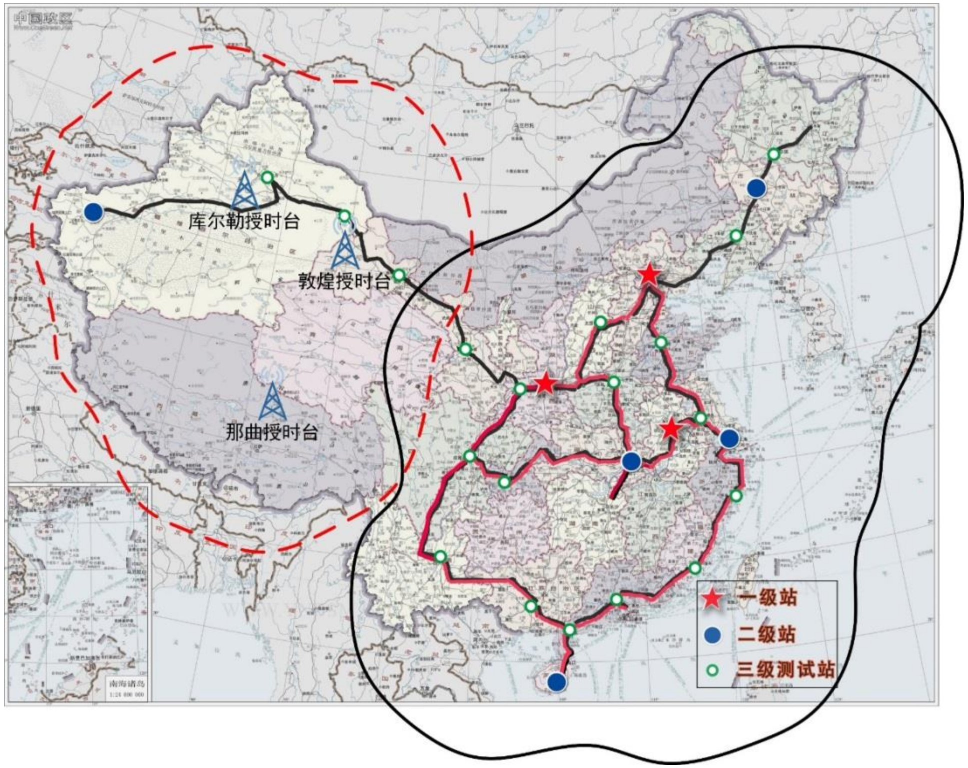
Across China fiber network of time and frequency

Precision land-based time service system

Projected completion in 2023

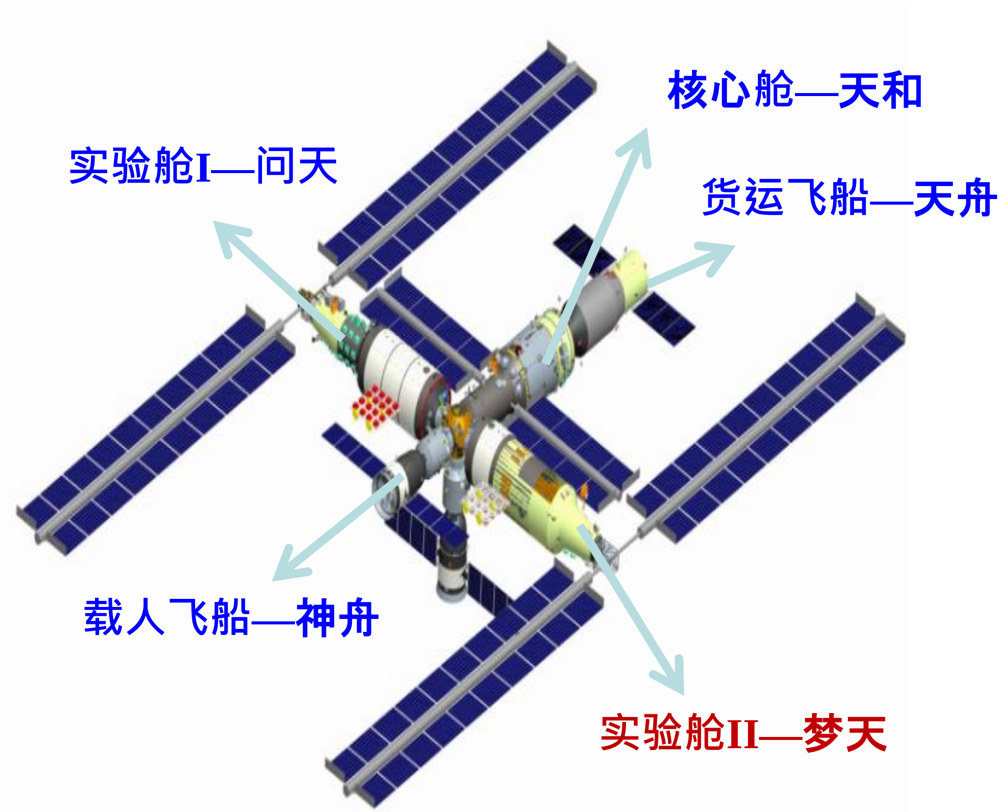
The part of Enhanced Loran (eLoran):

- 3 additional eLORAN stations built in the west of China, to realize the mainland coverage together with the existing eLORAN stations Connecting eLORAN station and differential station through optical fiber
- Accuracy of time service improved to 100ns by differential technique
- Broadcast Beidou Enhancement Information through eLORAN Station

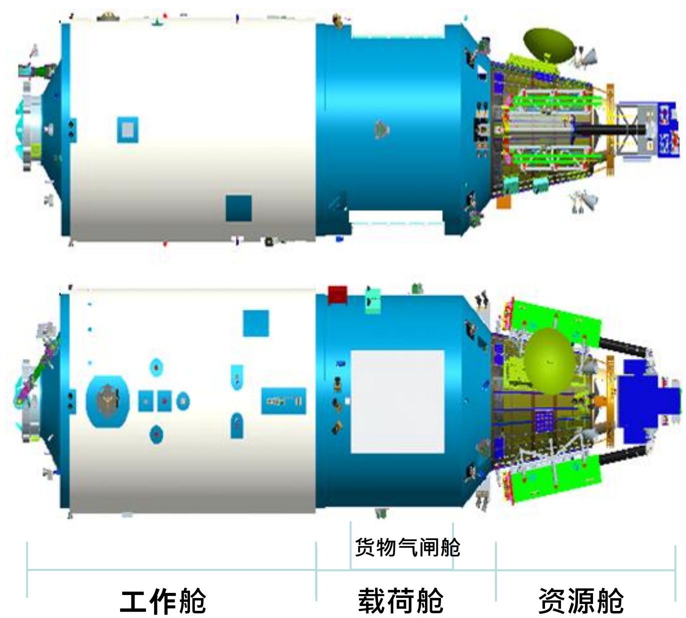


Chinese Space Station

Projected completion about 2022



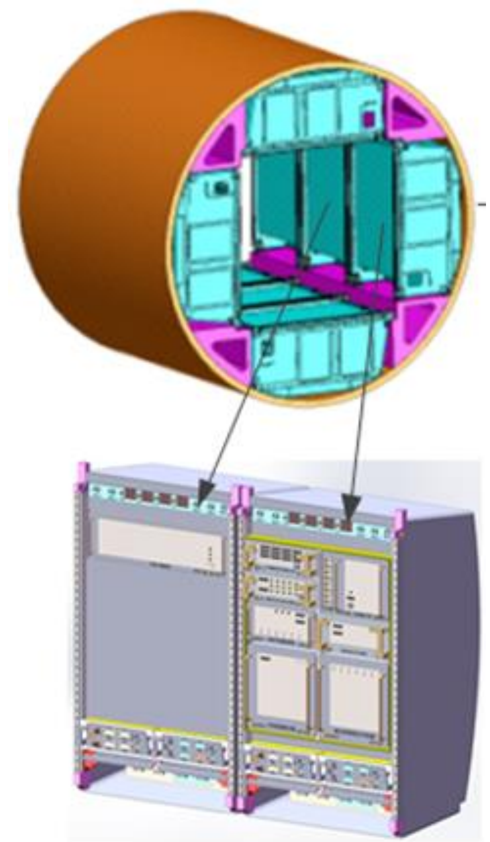
The basic configuration of the Chinese space station includes: core module, experimental module I and experimental module II



Experimental module Ⅱ "sky dream ", mainly supporting the experiments in the sealed cabin and the extravehicular test

Precision Time-Frequency system in Chinese Space Station

- Via integrating various atomic clocks, we can establish a spatial time-frequency generating-running system;
- Through the microwave and laser time-frequency transferring and comparing link, we can provide high-precision time-frequency signal to the ground and other districts;
- Key technologies and project design in progress



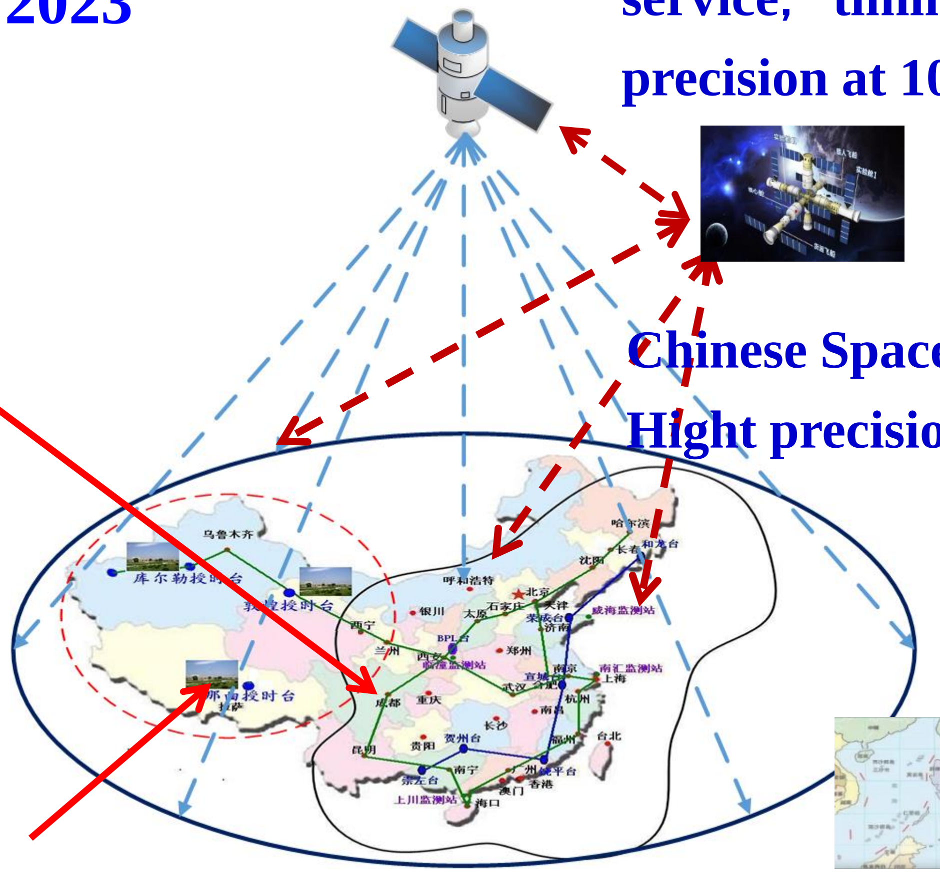
时频柜副柜　时频柜主柜

- **High Precision Time and Frequency Systems**
  - Active Hydrogen Maser
  - Cold Atomic Microwave Clock
  - Cold Atomic Optical Clock
  - Frequency Comparing System
  - Computer Controlling and communicating System
  - Microwave Transferring Link
  - Laser Transferring and comparing Link
  - GNSS

Space-ground time service system

Major science and technology infrastructure project in 2023

BeiDou, global PNT service, timing precision at 10ns



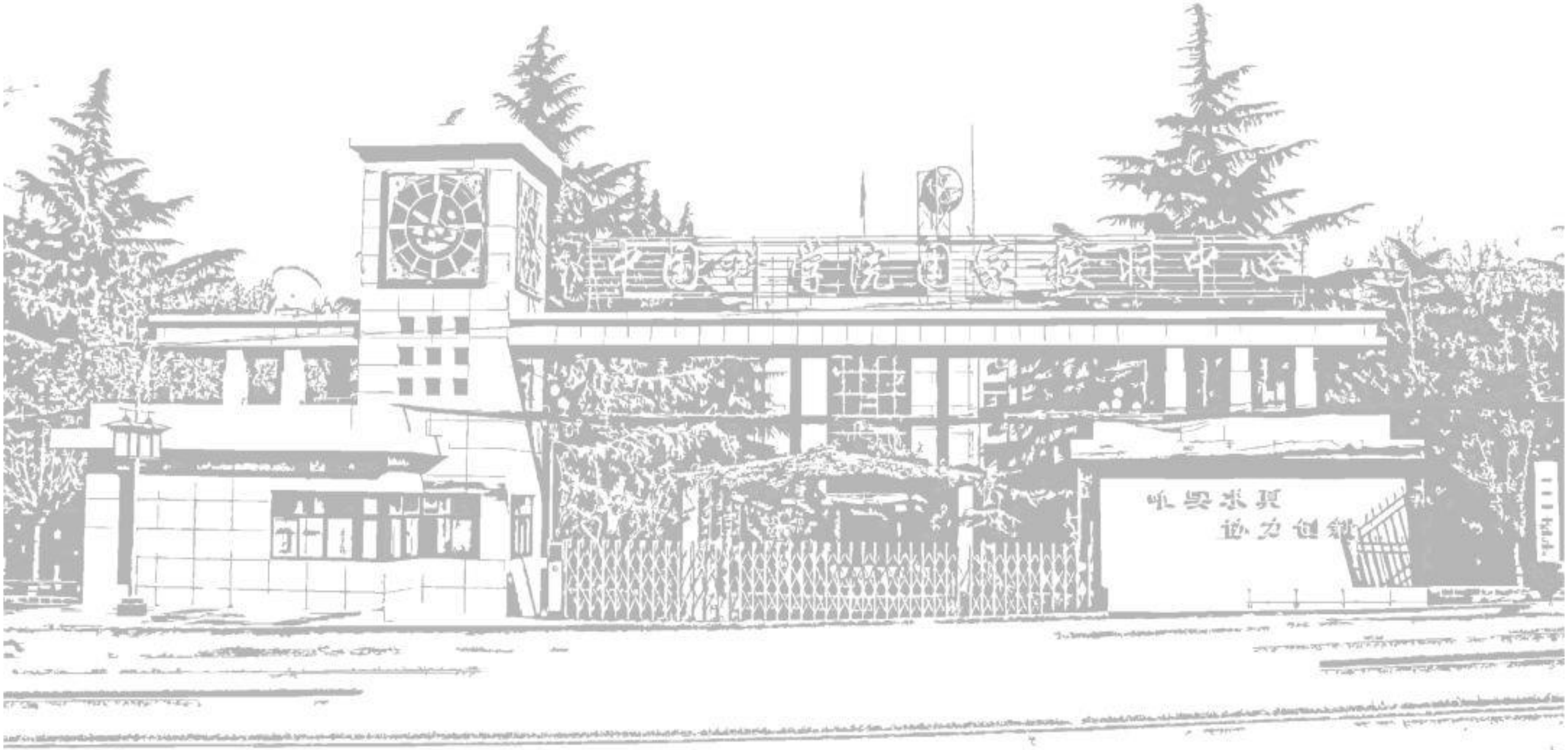
Chinese Space station : Hight precision T/F sys.

- **Fiber network cover main cities and users**
- **time transfer precision <100ps**
- **frequency transfer stability at E-19/d level**

eLORAN time service system

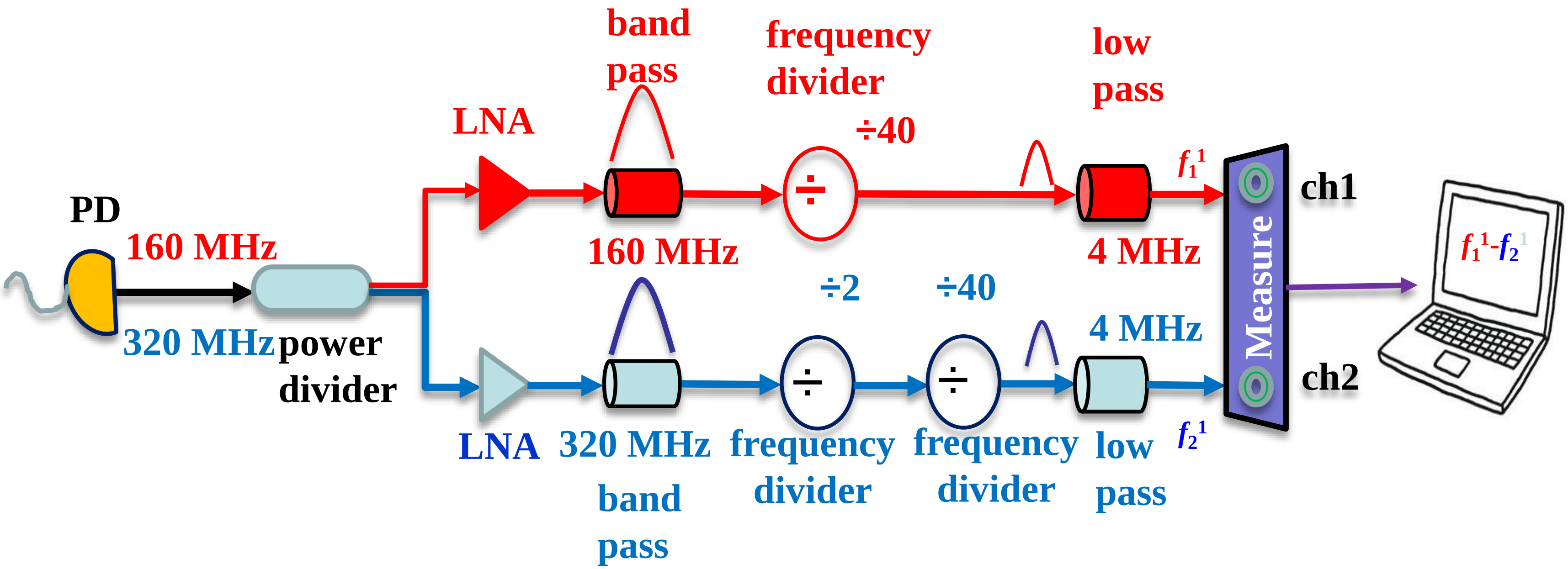
Precision in differential timing range< 100ns

Broadcast satellite timing correction, improved to ns level



Thank you for your attention!
Welcome to Xi’an

Data processing



$f_1 + f_2$=160 MHz

f_1^1 single trip frequency

4 MHz

Comparison

f_1^1-f_2^1

2($f_1 + f_2$)=320 MHz

f_2^1 round trip frequency

4 MHz

- 张老师，
- **1. JILA组的2015年锶光钟指标我重新核实并修改过了。**
- **2. JILA组17年的三维光晶格中的费米简并气体的最终指标5× 10-19为光钟测量精度。当然，由于该精度的光钟完全可以测出几个毫米的重力红移，所以采用一套光钟比对。**
- **3. 图中各实验室结果对比，JILA实验室17年结果采用虚线。**

ARTICLE

Received 14 Jan 2015 | Accepted 11 Mar 2015 | Published 21 Apr 2015

Systematic evaluation of an
2×10^{-18} total uncertainty

T.L. Nicholson[1,2], S.L. Campbell[1,2], R.B. Hutson[1,2], G.E. Marti[1,2],
M.D. Barrett[1,3], M.S. Safronova[4,5], G.F. Strouse[6], W.L. Tew[6] &

The pursuit of better atomic clocks has advanced many research are
quantum state control, new insights in quantum science, tighter lim
constant variation and improved tests of relativity. The record for the
accuracy is currently held by optical lattice clocks. Here we take an imp
realizing the full potential of a many-particle clock with a state-of-the-
^{87}Sr optical lattice clock now achieves fractional stability of $2.2 \times 10^{-}$
improved stability, we perform a new accuracy evaluation of our clo
systematic uncertainties that limited our previous measurements, such a
ac Stark shift, the atoms' thermal environment and the atomic response t
blackbody radiation. Our combined measurements have reduced the tota
JILA Sr clock to 2.1×10^{-18} in fractional frequency units.

REPORT

OPTICAL CLOCKS

A Fermi-degenerate three-dimensional optical lattice clock

S. L. Campbell,[1,2]* R. B. Hutson,[1,2]* G. E. Marti,[1] A. Goban,[1] N. Darkwah Oppong,[1]†
R. L. McNally,[1,2]‡ L. Sonderhouse,[1,2] J. M. Robinson,[1,2] W. Zhang,[1]§
B. J. Bloom,[1,2]|| J. Ye[1,2]¶

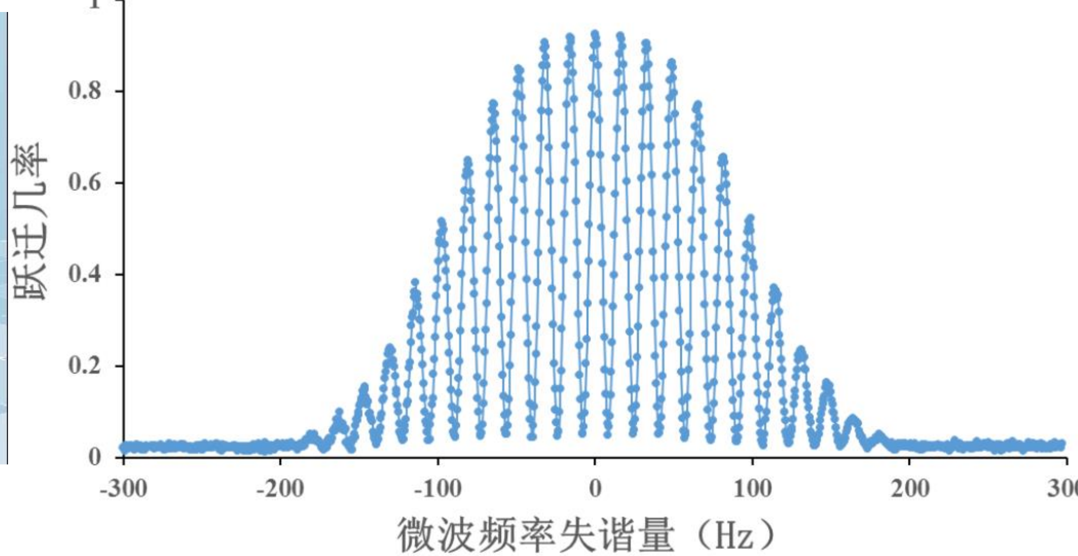
Strontium optical lattice clocks have the potential to simultaneously interrogate millions of atoms with a high spectroscopic quality factor of 4×10^{17}. Previously, atomic interactions have forced a compromise between clock stability, which benefits from a large number of atoms, and accuracy, which suffers from density-dependent frequency shifts. Here we demonstrate a scalable solution that takes advantage of the high, correlated density of a degenerate Fermi gas in a three-dimensional (3D) optical lattice to guard against on-site interaction shifts. We show that contact interactions are resolved so that their contribution to clock shifts is orders of magnitude lower than in previous experiments. A synchronous clock comparison between two regions of the 3D lattice yields a measurement precision of 5×10^{-19} in 1 hour of averaging time.

Atomic clocks are advancing the frontier of measurement science, enabling tabletop searches for dark matter and physics beyond the Standard Model (*1–4*), as well as providing innovative quantum technologies for other branches of science (*5*). One-dimensional (1D) optical lattice clocks provide a many-particle optical frequency reference that, together with advances in optical local oscilla- we loaded a two-spin degenerate Fermi gas into the ground band of a 3D optical lattice in the Mott insulating regime, where interactions are responsible for a suppression of doubly occupied sites (*18, 19, 21*). This enabled us to maximize atomic density while greatly suppressing collisional frequency shifts. For our coldest samples, the number of doubly occupied sites was suppressed by orders of magnitude relative to the increasing role of interactions relative to tunneling suppressed multiple occupancies in the Mott insulating regime. At the final lattice depths of 40 to 100 E_{rec}, where E_{rec} is the lattice photon recoil energy, the Lamb-Dicke requirement was satisfied for clock light along all directions (*25*). Spectroscopy was performed on the 698-nm $^1S_0(|g; m_F\rangle) \leftrightarrow {}^3P_0(|e; m_F\rangle)$ clock transition. The clock laser propagating along the $\hat{x}$ lattice beam was used for precision spectroscopy (Fig. 1A), whereas an oblique clock laser enabled a systematic characterization of the lattice by means of motional sideband spectroscopy (Fig. 1B). The absence of observable red-detuned sidebands demonstrated that the atoms were predominantly loaded into the ground band of the 3D lattice.

A long-standing question has been whether the overall ac Stark shift in a 3D lattice can be managed to allow state-of-the-art narrow-line clock spectroscopy. We implemented a solution to this challenge, inspired by the proposal in (*26*). The differential ac Stark shift from the lattice trapping beams at a particular trap depth $\mathcal{U}_0$ can be expressed in terms of its scalar, vector, and tensor components as

$$\Delta\nu = (\Delta\kappa^s + \Delta\kappa^v m_F \xi \hat{e}_k \cdot \hat{e}_B + \Delta\kappa^t \beta)\mathcal{U}_0 \quad (1)$$

where $\Delta\kappa^{s,v,t}$ are the scalar, vector, and tensor shift coefficients, respectively; ξ is the lattice light ellipticity; and $\hat{e}_k$ and $\hat{e}_B$ are unit vectors along the lattice beam wave vector and magnetic field quantization axis, respectively (*26, 27*). The parameter β can be expressed as $\beta = (3\cos^2\theta - 1)[3m_F^2 - F(F+1)]$, where θ is the angle between the nearly linear lattice polarization and $\hat{e}_B$.



15/09/2016

First Ramsey

V 1120mmx938.5mmx600mm + 680mmx938.5mmx600mm
M 330kg；
P 1300w

稳定度0.3ps@300s，1ps@1day

稳定度0.3ps@300s，1ps@1day

CACES