Activities Report To The 20_{th} Session Of The
Consultative Committee For Time And Frequency (CCTF)
National Institute of Metrology (NIM), China, September 2015

This report covers the activities of NIM in the following research areas:

1. **Cesium fountain clock**
2. **Time scale**
3. **Time and frequency transfer**
4. **Optical clock**
5. **Fiber comb**

1. Cesium fountain clock

1.1. Fountain clock NIM5
The NIM5 Cs fountain primary frequency standard was improved during the last 3 years mainly with respect to microwave-related frequency shifts and atom number stability. It has been used as a reference to steer TA(NIM), for measurements of the TAI scale unit and Sr optical clock frequency developed at NIM. A typical fractional frequency instability of 3×10^{-13} $(\tau/s)^{-1/2}$ is obtained when running at high atom density. The statistical uncertainty was calculated with the assumption of a white frequency noise for the total measurement intervals. A typical Type B fractional frequency uncertainty is 1.4×10^{-15}.

NIM5 started to report to BIPM since 2014, and totally 9 TAI scale unit measurements have been submitted to the BIPM. The respective durations of these measurements range from 15 to 30 days, and the operation rate is always better than 90%. The combined uncertainty ul/lab due to the link between the H271 and NIM5 and contribution from dead times is about 2×10^{-16}.

A comparison campaign of cesium fountain clocks from four national metrology institutes in Europe and Asia was carried out in May 2013. Six fountains at PTB, VNIIFTRI-SU, NPLI and NIM were compared by two-way satellite time and frequency Transfer (TWSTFT) and GPS Carrier Phase (GPS CP) techniques. NIM5 only operated 13 days during a 20 day campaign. The frequency differences between NIM5 and 5 other fountains are all less than 1.1×10^{-15}, which are agreed with 1σ of the combining uncertainties of the two compared fountain clocks and the uncertainty introduced by the comparison link.

1.2. Research work on the fountains
A new fountain is under developing since 2014. The atoms will be loaded into optical molasses from a 3D MOT, and optical pumping could be used to increase the number of atoms further. With a CSO based microwave synthesizer that is in the process of purchasing, we would expect to reach the shot noise, and reduce the instability of the new fountain to low $10^{-14}(\tau/s)^{-1/2}$.

A new microwave inspection system is also under developing in NIM. This system can be used not only in checking the performance of the microwave interferometer switch, but also monitoring the abnormal behaviors of the synthesizer.

2. Time scale

2.1. UTC(NIM)

Since the year of 2009, new UTC (NIM) was under construction at NIM's new campus, and it was switched to the new campus officially on October 14, 2012. The clock ensemble consists of 6 hydrogen masers (MHM2010) and 7 Cesium clocks (HP5071A, high-performance cesium beam tube). A stable Hydrogen maser is used as the master clock, and UTC (NIM) is generated from a micro phase stepper which is steered by the UTC(NIM) algorithm. UTC（NIM）is traced to UTC based on GNSS (Global Navigation Satellite System) time and frequency transfer and TWSTFT (Two-way Satellite Time and Frequency Transfer) system. Unfortunately the TWSTFT between Europe and Asia stopped due to the lifetime of the satellite.

The UTC(NIM) algorithm is based on the data of UTC and UTCr, H-maser ensemble frequency, and the NIM-5 fountain. In order to detect some sine-wave like fluctuation of NIM master clock other than the relatively stable drift, the algorithm based on the H-maser ensemble was introduced since 2015. The relative frequency differences between the H-maser ensemble and the master clock was evaluated, and then the fluctuation of NIM master clock was detected by the H-maser ensemble, as shown in Fig.1. Figure 2 shows the performance of the UTC (NIM) during Oct.14,2012 to Jul.31,2015, the data are from BIPM *Circular T*. In the year 2015, the time offset of UTC(NIM) from UTC is within ±5ns， and the time stability is about 0.3 ns/5d.

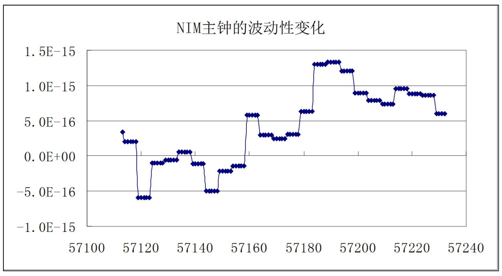

Fig. 1 fluctuation of NIM master clock

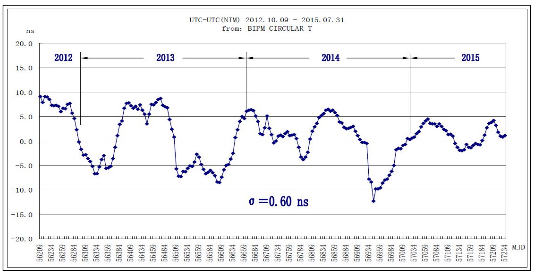

Fig.2 UTC-UTC(NIM)

2.2. Comparison of Cesium Fountain Clocks in Europe and Asia

A remote comparison campaign of cesium fountain clocks from four National Metrology Institutes in Europe and Asia was carried out in May 2013. Six fountains at Physikalisch-Technische Bundesanstalt (PTB) Germany, Scientific Research Institute of Physical-Technical and Radio Technical Measurements (VNIIFTRI-SU) Russia, National Physical Laboratory of India (NPLI) and National Institute of Metrology (NIM) China were compared by Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS Carrier Phase (GPS CP) techniques. The frequency differences and the comparison uncertainties between the compared fountain pairs were evaluated and are listed in Table 1. The comparison uncertainty (u) results from combining the uncertainties of the two compared fountain clocks and the uncertainty introduced by the comparison link. It has been shown that all the frequency differences between the fountains agreed within the 1-sigma uncertainty in the low 10^{-15} level.

Table 1: Mean frequency differences and comparison uncertainties (u) in parts of 10^{-15} between the fountains

Fountains	TWSTFT	GPS CP	u
PTB CSF1-NIM	0.3	-0.1	2.3
PTB CSF2-NIM	0.5	0.1	2.2
SU CSF1-NIM	0.2	-1.1	2.9
SU CSF2-NIM	0.5	-0.8	2.2
PTB CSF1-SU CSF1	-0.1	1.1	1.2
PTB CSF1-SU CSF2	-0.7	0.5	1.0
PTB CSF2-SU CSF1	-0.2	1.0	1.8
PTB CSF2-SU CSF2	-0.8	0.4	0.8
PTB CSF1-NPLI	1.2	1.0	2.6
PTB CSF2-NPLI	1.1	0.9	2.6
NIM-NPLI	0.0	0.5	3.3
SU CSF1-NPLI	1.1	-0.1	3.1
SU CSF2-NPLI	1.8	0.6	2.6

3. Time and frequency transfer

3.1. GNSS(Global Navigation Satellite system) time and frequency transfer

3.1.1. GPS(Global Positioning System) carrier phase time and frequency transfer

One GPS carrier phase processing method exclusively for time and frequency transfer, GPSTFP, was developed. Using this method, we implemented the CCD and long baseline time and frequency transfer experiments for performance verification. We can acquire a good agreement among P3 results, GPSTFP results, and the ones by the professional GPS processing software. From one day data, the difference between the mean values of P3 and GPSTFP results is less than 0.5 ns and the time stability from the CCD experiment is about 100 ps.

3.1.2. BDS (Beidou Navigation Satellite System) time and frequency transfer

Since 2003, the Beidou Navigation Satellite Demonstration System was officially brought into service. By the end of 2012, there are six GEO (Geostationary Earth Orbit), five MEO(Medium Earth Orbit) and five IGSO (Inclined Geosynchronous Satellite Orbit) satellites in orbit. Since 27th Dec 2012, BDS Signal in Space Interface Control Document-Open Service Signal B1I (Version 1.0) has been released. The developing BDS system with the partial coverage of Asia-Pacific area at present has provided the official service and can be used for time and frequency transfer in this area.

Time and frequency transfer method using code and carrier phase of BDS has been developed by NIM. The CCD and long baseline results are comparable with GPS. The standard deviation of the BDS P3 code and carrier phase results in the CCD experiment could be better than 1 ns and 100 ps with one day measurement. The combination of BDS and GPS code measurement for time and frequency transfer leads to the improved precision and robustness.

3.2. Two-Way Satellite Time and Frequency Transfer (TWSTFT)
The NIM01 TWSTFT earth station was established in 2008. Since May of 2009, NIM has participated the Europe-Asia TWSTFT link. At present, the participant laboratories of Europe-Asia TWSTFT link include PTB, TL, NICT, NIM, NTSC, SU and NPLI. For the Europe-Asia TWSTFT link using AM2 satellite, the time instability is below 1ns and the frequency stability is at the E-15 level. At present, NIM is going to control the surrounding temperature of the earth station, it is expected thta the time and frequency uncertainty will be improved after the work is finished.

3.3. Optical fiber time and frequency transfer
From NIM’s Changping new campus, we have three fiber links including the link between the two campuses of NIM, the link between Changping campus and Beijing Satellite Navigation Center (BSNC), and the link between Changping campus and Tsinghua University (THU). In the near future, within the range of 100 km, based on Changping campus, we might build more links with several important metrology and research institutes, which have the requirements for precise time and frequency transfer referenced to NIM.

3.3.1. Frequency standard signal transfer via fiber
Our fiber frequency standard signal transfer systems were built based on the DMTD (Dual Mixer Time Difference) method as NICT used. A higher modulation frequency up to 9.2GHz is used to modulate the 1.55um optical carrier, which increases the system sensitivity to fiber induced phase noise.Temperature control systems are added to both the local end and the remote end of all the fiber transfer setups,which restrain the non common noise induced by single pass fiber.

Three fiber transfer systems were built and two of those were used to distribute the standard frequency signal from NIM Changping campus to Hepingli campus and BSNC respectively. The other one was used to test the stability of the transferred standard frequency signal by the cascaded transfer method. For these two links, the stability of the transfer systems is better than 1E-14@1s, 1E-17@1day. We have transferred our master H maser signal from NIM changping campus to BSNC. The comparison between UTC(NIM) and UTC(BSNC) is carrying out based on the fiber frequency transfer setup. NIM’s optical clock tracing to the NIM5 fountain clock is also fulfilled by this more directly method instead of the GNSS method.

3.3.2. TWOTFT (two way optical fiber time and frequency transfer)
TWOTFT has been studied and implemented according to the similar principle of

TWSTFT. We initially constructed the experiment system for TWOTFT and did some experiments such as time and frequency transfer through the laboratory optical fiber and the real optical fiber links including the real link with 109 km length at NIM. We can get the time stability of less than 6 ps/s and 0.9 ps/100s, and the standard uncertainty of less than 200 ps for time transfer.

3.4. Time link calibration

Since Oct 14th 2012, we have changed our UTC(NIM) to the new campus. In order to contribute to the realization of TAI with low uncertainty, a calibration of the time transfer link between NIM and PTB is needed. IMPR receiver (Septentrio PolaRx2eTR) located at the old campus has been calibrated since the end of 2009 by BIPM and we used it as the reference receiver to calibrate IMEU with the differential calibration. Shortly After that, IMEU was moved to the new campus and calibrated the two GNSS time and frequency transfer receivers including IMEJ(Dicom GTR50) and BJNM(Septentrio PolaRx3eTR). In June 2014, the time transfer links and IMEU of NIM have been successfully calibrated again by BIPMthe and the results agree well with those acquired by the self-calibration of NIM in 2012.

Since 2014 NIM has also started to design and develop one kind of homemade calibration system for the time link calibration on the basis of NIMTFGNSS-2 receiver. The system has been constructed preliminarily and calibrated, at the same time we have written the guideline for APMP calibration using this calibrator and in the near future, with this calibrator we may implement the calibration campaign of some TAI links under the APMP(Asia Pacific Metrology Programme) scheme.

In 2014 and 2015, NIM sent IMEU to BSNC for the calibration of their time transfer receivers. During the calibration, we implemented the differential calibration between IMEU and BSNC GPS time transfer receivers, INTDLY values of BSNC receivers for two times have been in good agreement with each other.

3.5. Real time remote calibration(RTRC) for time and frequency

Using GNSS time and frequency transfer receiver NIMTFGNSS-1, RTRC by GNSS code based time and frequency transfer has been realized. As the extension of RTRC, NIM can provide one low-cost Rubidium oscillator disciplined by UTC(NIM) in near real-time, NIMDO. Its performances have been verified and demonstrated at the two campuses of NIM. Referenced to UTC(NIM) and averaged for one day, we acquired that the time and frequency accuracy of NIMDO could be better than 5 ns and 1e-13 respectively, the time and frequency stability could be better than 5 ns and 6e-14 respectively. We have set up four NIMDOs at four cities (Urumchi, Guiyang, Harbin, and Beijing) in China to reveal the longer baseline effects. In the near future, based on some study and application on time and frequency transfer by BDS and multiple GNSS systems, we would enhance the measurement accuracy and stability. We are trying to lower the noise of time and frequency transfer system in NIMDO by using GPS carrier phase method in near real time. Certainly, on the basis of the present NIMDO principle, we could study and form the NIMDO based on the Cesium clock, the Hydrogen maser, or some other atomic clock to meet the applications with the higher level requirements.

4. Optical clock

A strontium optical lattice clock based on ^{87}Sr is being built and evaluated at NIM. The atoms experience two stages of laser cooling before being loaded into a horizontal 1-dimensional optical lattice at the magic wavelength of 813 nm[21]. The atoms are then interrogated by a narrow linewidth 698 nm laser and the excitation rate is measured to calculate the frequency difference between the laser and the clock transition, and this frequency error is used to lock the 698 nm laser to the ultra narrow $^1S_0$-$^3P_0$ clock transition[22,23,24].

The frequency corrections and uncertainties of the Sr optical lattice clock have been evaluated. The total systematic uncertainty of the Sr optical clock is evaluated to be 2.3×10^{-16}. In order to measure the absolute frequency of the Sr optical clock with respect to NIM's cesium fountain clock NIM5, the frequency of a flywheel H-maser of NIM5 is transferred to the Sr laboratory through a 50 km fiber. A fiber optical frequency comb, phase locked to the reference frequency of this H-maser, is used for the optical frequency measurement. The absolute frequency of NIM's Sr optical clock is 429228004229873.7(1.4) Hz[24].

5. Fiber comb

Based on optical amplification, frequency doubling and spectrum broadening, a home-made Er-fiber femtosecond optical frequency comb (Er-FOFC) with output wavelengths covering visible light is demonstrated. One path with an average power of 8 mW from Er-FOFC is first amplified to 532mW by injecting into an Er-doped femtosecond fiber amplifier and then frequency doubled in a MgO：PPLN crystal with an output power of 170mW. The frequency-doubling light is spectrally broadened from 500nm to 1000nm in a photonic crystal fiber. To verify the performance of the broadened spectrum, the light from the Er-FOFC and a compact iodine-stabilized frequency-doubled Nd: YAG laser at 532 nm is beaten. A beat signal with a signal-to-noise ratio (SNR) of 30dB at 100kHz RBW is obtained.

An Er-FOFC with a tunable wavelength output from 689 to 813 nm based on the single-point frequency-doubling (SPFD) technique is demonstrated. The spectrum of the Er-FOFC covers the wavelengths of the strontium atomic and the calcium ionic optical clock lasers. Meanwhile, a beat frequency signal between the Er-FOFC and a tested laser at 698nm or 729 nm with a SNR of 30 dB at 100kHz RBW is obtained.

Based on home-made comb, we also begin to carry on the research on absolute distance measurement and high-resolution optical spectroscopy.

Publication and presentation list:

1. Fang Fang, et al., "NIM5 Cs fountain clock and its evaluation", Metrologia,52,

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2. Fang Fang, et al., "Design of the new NIM6 fountain with collecting atoms from a 3D MOT loading optical molasses", IFCS 2015
3. Fang Fang, et al., "Accuracy Evaluations of the Cs Fountain Primary Frequency Standard NIM5",IFCS, 163(2014)
4. Yu Zhang, et al., "Thermal effect of the microwave Mach-Zehnder interferometric switch", IFCS,376 (2014)
5. Fang Fang, et al.,"Accurate Evaluation of Microwave-Leakage-Induced Frequency Shifts in Fountain Clocks", CHIN. PHYS. LETT. 31, 100601(2014)
6. Fang Fang, et al., "Reducing the Blackbody Radiation Shift in the NIM New Fountain Design", IFCS, 233(2013)
7. Nianfeng Liu, et al.,"Accuracy Evaluations of NIM5 Cs Fountain Clock", CHIN. PHYS. LETT. 30, 010601(2013)
8. Kun LIANG, et al., "Developing of one time link calibrator with GNSS at NIM", IFCS&EFTF2015
9. Kun LIANG, et al., "Preliminary time transfer through optical fiber at NIM", IFCS&EFTF2015
10. ZHU Xiangwei, et al., "The Research Progress of Two Way Time Synchronization with Fiber Based on Spread Spectrum Signal", IFCS&EFTF 2015
11. Kun LIANG , et al., "Disciplined Oscillator System by UTC(NIM) for Remote Time and Frequency Traceability", EFTF 2014
12. Kun LIANG, et al., " New Timekeeping System and its Time Link Calibration at NIM", IFCS 2014
13. Aimin ZHANG, et al., "Comparison of Caesium Fountain Clocks in Europe and Asia", EFTF 2014
14. Aimin Zhang, et al., "Research on Modification of H-maser Drift", IFCS 2014
15. Yang Zhiqiang, et al., "Research on Calibration of TWSTFT Link by GPS", Proceeding of IFCS-EFTF 2013.
16. Kun Liang, et al., "Real-Time Remote Calibration (RTRC) System for Time and Frequency", Proceeding of IFCS-EFTF 2013.
17. Kun Liang, et al., "Preliminary Implementation of Time and Frequency Transfer by BDS", Proceeding of IFCS-EFTF 2013.
18. Aimin Zhang, et al., "Reconstruction of UTC(NIM)", Proceedings of IFCS-EFTF 2013.
19. Aimin Zhang, et al., "Research on Time Keeping at NIM", Journal of Metrology Society of India, Volume 27, Number 1 (2012), 55-61.
20. Kun Liang, et al., "GPS Carrier Phase Time Transfer Using a Modified Solution Model", IFCS 2012
21. Yige Lin, et al., "Magnetic Field Induced Spectroscopy of ^{88}Sr Atoms Probed with a 10 Hz Linewidth Laser," Chinese Physics Letters, vol. 30, no. 1, p. 014206, Jan. 2013.
22. Ye Li, et al., "A Hertz-Linewidth Ultrastable Diode Laser System for Clock Transition Detection of Strontium Atoms," Chinese Physics Letters, vol. 31, no. 2,

p. 024207, Feb. 2014.
23. Qiang Wang, et al., “Observation of Spin Polarized Clock Transition in ^{87}Sr Optical Lattice Clock,” Chinese Physics Letters, vol. 31, no. 12, p. 123201, Dec. 2014.
24. Yige Lin, “First Evaluation and Frequency Measurement of the Strontium Optical Lattice Clock at NIM,” Chinese Physics Letters, vol. 32, no. 9, p. 090601, Sep. 2015.
25. Qiang Wang, et al., "Preliminary Lock of the Strontium Lattice Clock Based on ^{88}Sr Atoms", Asian Pacific Workshop for Time and Frequency, Taipei, Taiwan, Oral presentation, 2013
26. Yige Lin, et al.,“Sr Optical Lattice Clock Research at NIM,” Joint IEEE International Frequency Control Symposium and European Frequency and Time Forum, Prague, Czech Republic, Poster session, 2013
27. Yige Lin, et al., “Progress of the Strontium Optical Clock at NIM,” Joint IEEE International Frequency Control Symposium and European Frequency and Time Forum, Denver, USA, Poster session, 2015
28. Fei Meng, et al.,“Application of an Er:doped fiber comb for Sr lattice clock,” Chinese Journal of Lasers, 2015, 42(7): 0702012
29. Hanzhong Wu, et al.,“Spectral interferometry based absolute distance measurement using frequency comb,” Acta Physica Sinica, 2015, 64(2): 020601
30. Baike Lin, et al., A compact Iodine-stabilized solid-state laser at 532 nm”, Chinese Journal of Lasers, 2014, 41(9): 0902002