Report to the 19th Meeting of CCTF

Research Activities on Time and Frequency
National Metrology Institute of Japan (NMIJ)/AIST

The National Metrology Institute of Japan (NMIJ) is responsible for almost of all physical and chemical standards and for related technologies in Japan. The Time and Frequency Division of NMIJ is in charge of time and frequency metrology. Three sections, Time Standards Section, Frequency Measurement Systems Section, and Wavelength Standards Section, are making research and development in time and frequency standards field. We describe the recent activities of these three sections in this report.

1. Cs Atomic Fountain Frequency Standards

NMIJ-F1 has been a primary frequency standard with an uncertainty of 4×10^{-15} since 2004. From the previous CCTF, we have reported the data to Bureau International des Poids et Mesures (BIPM) 7 times by operating NMIJ-F1 due to the progress in the stability and the reliability of the whole system [1]. However, the operation of NMIJ-F1 has stopped due to the huge earthquake and depletion of a cesium reservoir since March 2011.

The second fountain, NMIJ-F2, is under construction to achieve less than 1×10^{-15} in uncertainty [1]. After the modification of the optical-molasses configuration from (111) to (001) and the improvement of the vacuum, we launched up 2×10^{7} atoms with a temperature of 1 uK and observed Ramsey fringes with 1×10^{5} detected atoms. There is an advantage in the cooling laser power, which reaches 100 mW per beam.

In addition, we proposed the truncated atomic beam fountain to achieve both a low collisional frequency shift and high frequency stability [2]. In this fountain, a cold atomic beam is launched up, and turned off just before its top reaches a Ramsey cavity. By this method, a dilute and long cold atomic cloud can be obtained, suppressing a light shift during the interrogation.

2. Cryogenic Sapphire Oscillator and calibration service of phase noise

Two units of cryogenic sapphire oscillators (CSOs) have been maintained as local oscillators for the Cs atomic fountain frequency standards and for the evaluation of ultra-stable lasers in optical lattice clocks.

A phase noise standard with a carrier frequency of 10 MHz and phase noise of -100 dBc/Hz was developed using a CSO as a reference oscillator [3]. The calibration service of phase noise for phase noise measurement apparatus started in 2011 at Fourier frequencies of 1 Hz, 10 Hz, 100 Hz, 1 kHz, 10 kHz and 100 kHz.

3. Time keeping

There are 6 Cs atomic clocks including non-operational ones and 4 H-maser standards to maintain UTC(NMIJ). All Cs clocks and H-masers failed to operate properly on March 11th, 2011 due to the east Japan huge earthquake disaster. Since then we have been trying to recover those clocks and the related systems. Now we are reporting the data of 3 Cs clocks and 3 H-masers to BIPM every month. The source oscillator of UTC(NMIJ) is one of the 3 H-masers since 2006. One H-maser could not recover well. We will introduce a new maser in the fiscal year 2012. Temperature controlled chambers for clocks are working well to keep the inside temperature within 0.2 K of peak-to-peak variation. Frequency steering using AOG has been done appropriately. These activities resulted in generating stable UTC(NMIJ) within ±18 ns to UTC in 2011. Relative frequency of UTC(NMIJ) to UTC has been kept within $\pm 1.4\times10^{-14}$ in 2011 as shown in Fig. 1.

4. Time and Frequency transfer

We use GPS P3 method for the international time and frequency transfer to contribute to the TAI using Z12-T. NMIJ has been participating in the pilot experiment by the BIPM for producing a rapid UTC (UTCr) since January 2012. NMIJ is also maintaining TWSTFT facilities to link Asian institutes and PTB. The 19th meeting of the CCTF working group on TWSTFT was held at NMIJ on 12-13 September 2011.

For the development of precise time transfer techniques, we have been studying about carrier phase TWSTFT method and frequency transfer system using optical fiber cable. A precise frequency comparison system was developed using dense-wavelength division multiplexing (D-WDM) technologies. The key component is a new bi-directional optical amplifier that can overcome the fiber loss limits. The proposed optical amplifier has an optical isolator in each two-way-channel divided by wavelength filters, to suppress the optical reflection that causes amplification instability [4]. Experimental result shows stability of 8×10^{-17} at 10^5 s in a fiber link of 160 km in total with one bidirectional optical amplifier [5]. Recently, we are studying about the system using fiber stretchers for distributing multiple signals with femtosecond stability. The recorded propagation time fluctuations are 10.4 fs and 2.8 fs r.m.s. for the 1 G and 10 GHz signals, respectively in the system using 400 m silica fiber (Fig. 2). The Allan deviations are 2.7×10^{-19} (1 GHz) and 6.0×10^{-20} (10 GHz) for the averaging time of 10^5 s as shown in Fig. 3.

5. Calibration service

NMIJ provides frequency calibration services for both in-house and remote facilities. The CMC is 5×10^{-14} for in-house and 1.1×10^{-13} (Baseline: 50 km), 1.4×10^{-13} (Baseline: 500 km) and 4.9×10^{-13} (Baseline: 1600 km) for remote calibration, respectively. As remote frequency calibration service, traditional GPS common-view method is used in the system. It consists of a user equipment, a data transfer protocol, and a data processing system. Now we are offering the service to 14 remote users. Fig. 4 shows the long-term characteristics of the services to each user. The experimental standard deviations were almost less than 1×10^{-13} level for about 2 years. This result shows the excellent long-term capability with small uncertainty of calibration.

6. Yb optical lattice clock

Since the first measurement of the absolute frequency of the ^{171}Yb optical lattice clock [6], we have been working on lattice laser frequency stabilization, and excitation ratio measurement to obtain atomic spectra with a higher signal-to-noise ratio. We use a light source for the clock transition at 578 nm that is stabilized to a vertical cavity made form ultra low expansion glass [7]. A light source emitting at 556 nm is use for the second-stage cooling, which is phase locked to a fiber-based optical frequency comb [8]. We have performed an improved absolute frequency measurement of the $^1S_0$ - $^3P_0$ clock transition of the ^{171}Yb optical lattice clock. The absolute frequency is determined as 518 295 836 590 863.1(2.0) Hz relative to the SI second [9].

7. Sr optical lattice clock

Development of a Sr optical lattice clock is in progress at the NMIJ. The clock operates with lattice-confined ^{87}Sr atoms with nuclear spin $I = 9/2$. After two-stage laser cooling (using the $^1S_0$-$^1P_1$ [10] and then the $^1S_0$-$^3P_1$ [11] transitions), about 10^3 atoms were loaded on a vertically oriented one-dimensional (1D) optical lattice operating at a magic wavelength. We perform spectroscopic observations of the 698-nm clock transition of ^{87}Sr using a laser linewidth transfer method. A narrow linewidth fiber-type optical frequency comb [12, 13] is employed to transfer the Hz-level linewidth of the 1064-nm ultrastable laser to an extended cavity diode laser at 698 nm. We have stabilized the clock laser using the observed Sr atomic spectra. We are now measuring the absolute frequency of the ^{87}Sr optical lattice clock.

8. Fiber frequency comb

Several types of fiber-based frequency comb system have been developed in NMIJ. The conventional type contains 4 braches for different applications and can be operated over a continuous period of more than one month. We demonstrate that fiber-based frequency combs with an intracavity electro-optic modulator can transfer both linewidth and frequency stability to another wavelength at the millihertz level [12, 13]. Our measurement capability for optical frequencies using a frequency comb has been registered in CMC. One of the comb systems is used as the national standard of length in Japan.

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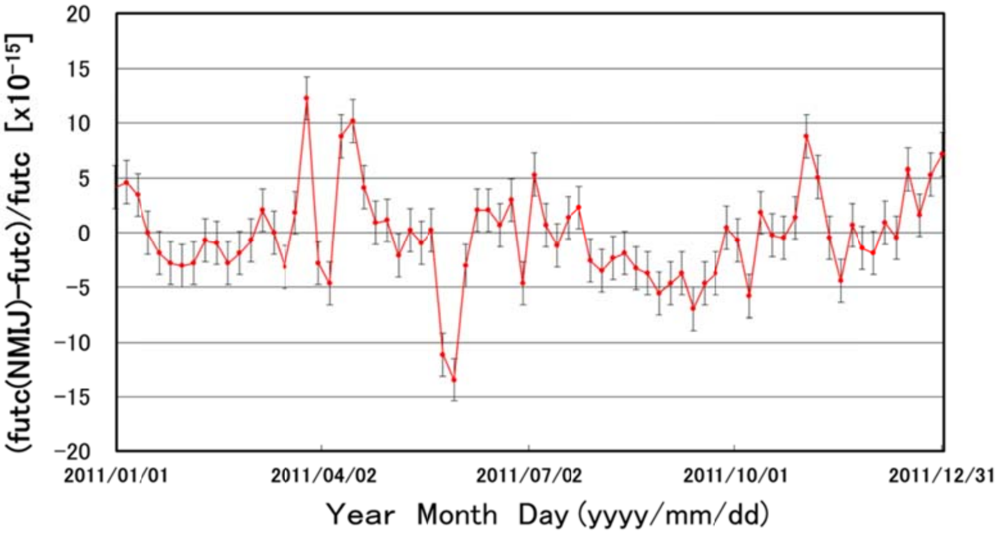

Fig. 1 Relative frequency offset of NMIJ to UTC in 2011.

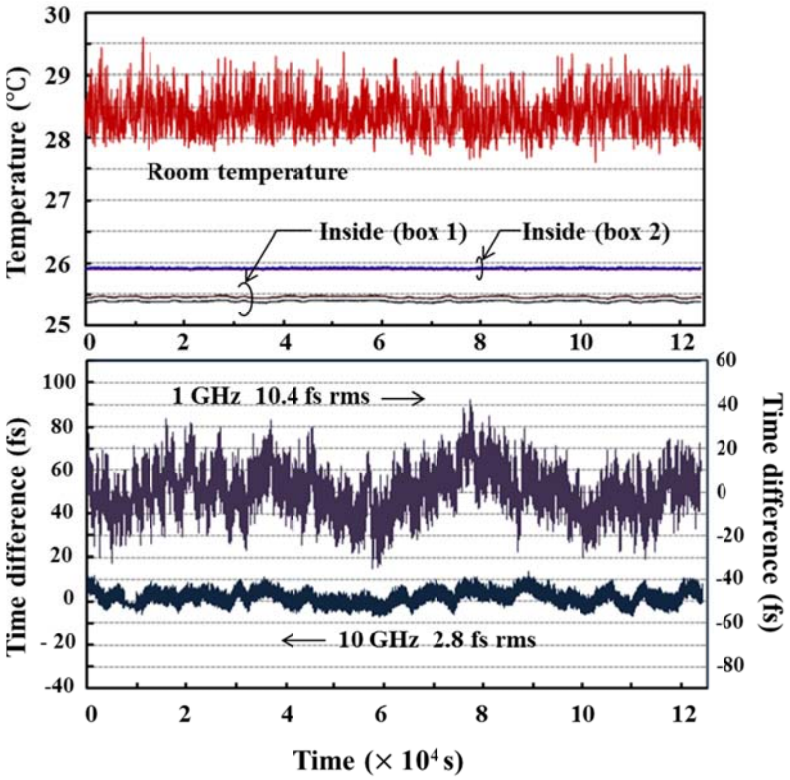

Fig. 2 Propagation delay fluctuation and temperature.

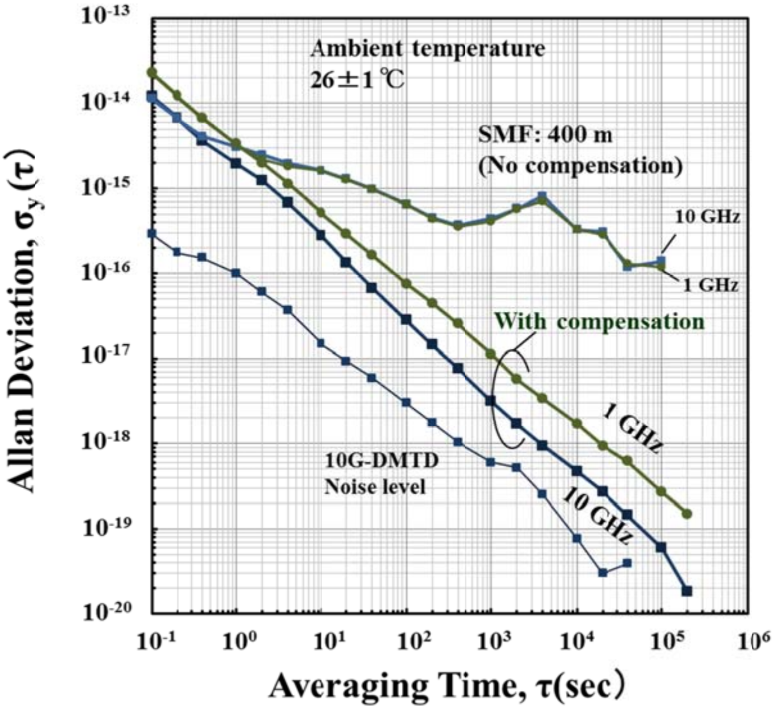

Fig. 3 Long-term frequency stability of the distribution system.

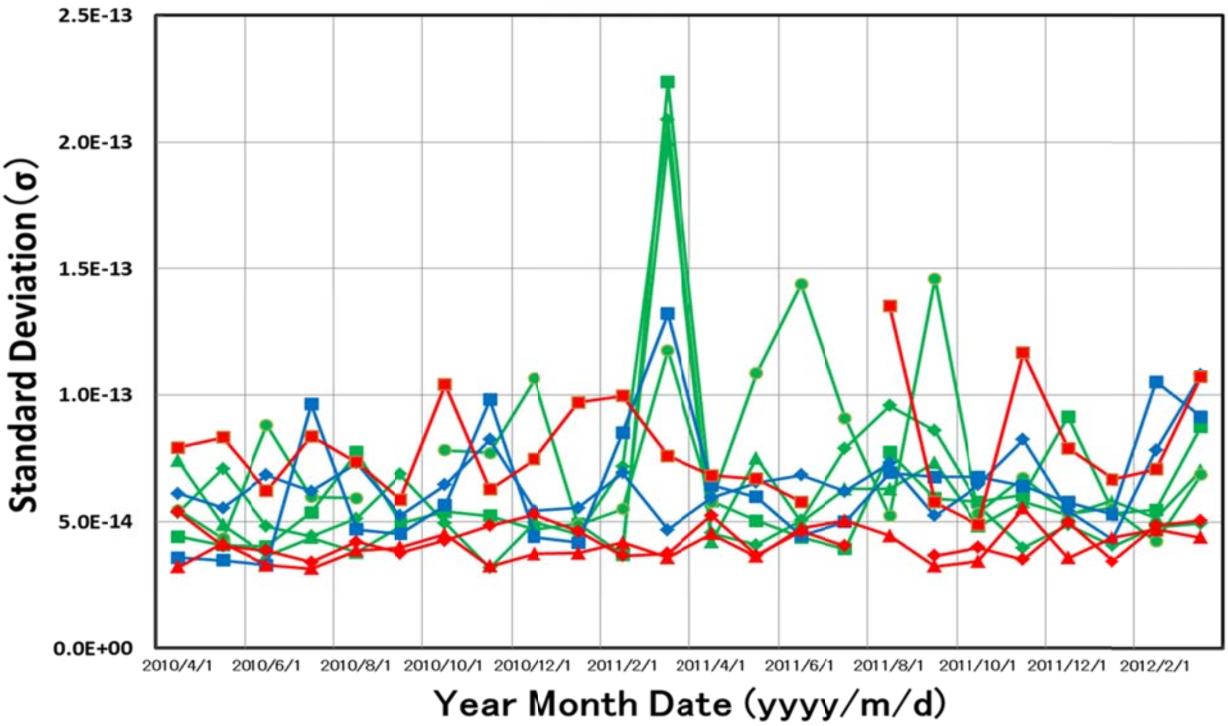

Fig. 4 Long-term characteristic of frequency remote calibration service.