

Report to the 17th Session of CCTF

Research Activities on Time and Frequency

National Metrology Institute of Japan (NMIJ) / AIST

The Time and Frequency Division of NMIJ is responsible for the Japanese national standard of time and frequency. During the two years since the last CCTF we have put forward the developments and improvements of primary frequency standards, NMIJ-F1 and NRLM-4. The time scale of UTC(NMIJ) has been modernized by implementation of hydrogen masers, and calibration activities, such as remote calibrations, have been widely expanded. In the field of optical frequency, activities on new types of optical frequency standards, such as optical lattice clocks, have been enhanced. In addition progress was made in new technologies such as optical fiber combs.

1. Cs Atomic Fountain Frequency Standard, NMIJ-F1

In 2005, NMIJ started the operation of NMIJ-F1 as a primary frequency standard. The design, the basic performance and the preliminary evaluation of NMIJ-F1 are described in Ref.[1]. The resulting uncertainties are larger than the preliminary evaluation [1], because the operational conditions are different from previous experiments. The conditions will be improved and the uncertainty will be reduced in future.

Three measurements, each of a period of ten days, were reported. The evaluated uncertainties u_A , $u_{link/lab}$, u_B are briefly described in the following.

Type A uncertainty u_A

The NMIJ-F1 uses an optical molasses to load the atoms, and its frequency stability, $\sigma_y(\tau)$, is about $1 \times 10^{-12} \tau^{-1/2}$. The measurement uncertainty based on the frequency instability is 1.1×10^{-15} , assuming white FM noise over the comparison period of 10 days.

Uncertainty of the link in the laboratory $u_{link/lab}$

The uncertainty due to the link in the laboratory, $u_{link/lab}$, consists of two factors as written in the following equation

$$u_{link/lab} = \sqrt{u_{dead\ time}^2 + u_{link/maser}^2}$$

where $u_{link/maser}$ is the uncertainty due to the noise of the phase comparator between the fountain and the hydrogen maser, and $u_{dead\ time}$ is the uncertainty due to the operational dead time of the fountain. The $u_{link/maser}$ was 0.5×10^{-16} over a period of 10 days. NMIJ-F1 was operated almost continuously with an efficiency of over 90 %. The

operation was occasionally interrupted due to earthquakes, electric power failures and so on. The $u_{dead\ time}$ was approximately 10^{-16} for three frequency comparisons of TAI and NMIJ-F1.

Type B uncertainty u_B

The following table shows the uncertainty budgets that were used for the frequency comparison during MJD 53589-53599. Type B uncertainty is contributed to by the following five factors [1,2,3] and totals 4.0×10^{-15} . It is mainly limited by the estimation of cold collisional frequency shift.

Source of uncertainty	Bias	Uncertainty
2 nd order Zeeman	181.7	2.0
Blackbody radiation	-17.2	0.9
Gravitation	1.6	0.1
Cold collisions	0.0	3.3
Distributed cavity phase	-	1.2
Total	166.1	4.0

In 2006 the microwave system for Ramsey interrogation was modified in order to improve its reliability. The frequency difference between the center of the Ramsey fringe and the hydrogen maser is estimated from the control record of the Direct Digital Synthesizer that is a part of the synthesis chain. A new pulse pattern generator was also introduced for sequential control of NMIJ-F1. With the new pulse pattern generator many parameters, such as launch height, sequence cycle in the fountain, and shutter timing, are easily changeable.

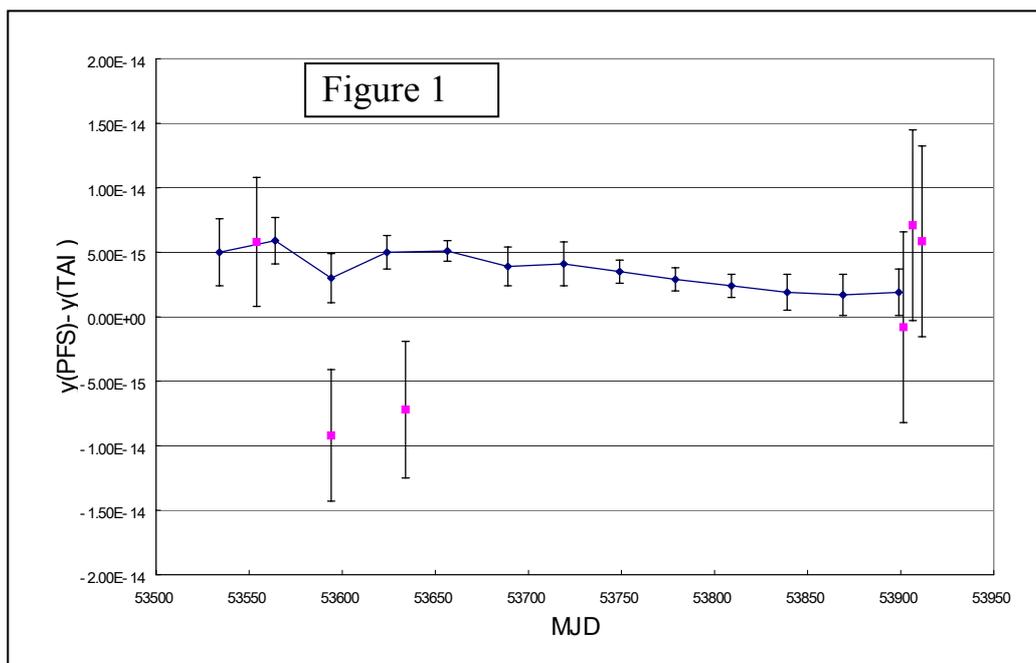


Figure 1 shows frequency comparison between NMIJ-F1 and TAI from MJD 53549(28/06/2005) to 53914(28/06/2006). The square data points indicate frequency

difference between NMIJ-F1 and TAI. The first three measurements were published in Circular T. The last three measurements were each taken over a period of five days. Uncertainties of each measurement, including the uncertainty of a link to TAI, are estimated by a conventional method. The diamond-shaped data points show the frequency difference between PFS and TAI.

Informally, comparisons are being made between the frequency of NMIJ-F1 and TAI, as shown in Figure 1. Also, the power dependence of microwave for Ramsey interrogation is being investigated. We will be able to restart the formal comparison between the NMIJ-F1 and TAI in a few months.

2. Optically Pumped Cs Beam Frequency Standard, NRLM-4

The optically pumped cesium beam frequency standard, NRLM-4, was operating as a primary frequency standard from February 1998 [4] to November, 2000. Its operation restarted this year. The previous uncertainty of 2.9×10^{-14} was due to the distributed cavity phase shift. In order to reduce this uncertainty, the Ramsey cavity was replaced with an H-bend ring cavity. In the H-bend cavity the direction of C-field and oscillating microwave field is perpendicular to the Cs beam propagation direction. The uncertainty, at a level of 1×10^{-14} , is being reevaluated in order to restart the report to BIPM in a few months.

3. Cryogenic Sapphire Oscillator

Two cryogenic sapphire oscillators (CSOs) have been developed for use as a local oscillator for the Cs atomic fountain and as a reference signal for a femtosecond mode-locked laser. The CSOs employ a loop oscillator configuration, which is controlled by a Pound-type frequency stabilization scheme and a power control servo. These oscillators exhibited a fractional frequency stability of 1.1×10^{-15} at an averaging time of 1 s [5]. For averaging times between 2 s and 640 s the measured oscillator fractional frequency instability was below 10^{-15} with a minimum of 5.5×10^{-16} at an averaging time of 20 s.

Optical frequency synthesis from a CSO has been implemented using a fiber-based frequency comb. The synthesized optical frequency exhibited an Allan deviation of $\sim 6 \times 10^{-14} \tau^{-1/2}$ for averaging times between 1 s and 100 s. A minimum frequency instability of 3.0×10^{-15} at an averaging time of 1280 s was observed by comparing a rubidium two-photon stabilized laser. The short-term frequency stability was limited by the rubidium two-photon stabilized laser [6].

4. Time scale of NMIJ

UTC(NMIJ) was generated by the master clock method using one of the Cs clocks until May, 2004. From June, 2004 to February, 2006, the UTC(NMIJ) was steered using an AOG with a Cs clock as its source. In March, 2006, the Cs clock was replaced by a hydrogen maser as the source oscillator for the AOG to generate

UTC(NMIJ). Accordingly, the short term stability and uncertainty of UTC(NMIJ) have been extremely improved. It is used for the evaluation of the primary frequency standards and optical frequency measurements, and as the reference signal for frequency traceability for industrial clients.

5. Time and frequency transfer

In order to contribute to the keeping of TAI, we have been using a Z12-T, a dual frequency GPS receiver, for global time and frequency transfer. We also have been participating in the two-way satellite time and frequency transfer link in Asia-Pacific region using JCSAT-1B and a multi-channel TWSTFT modem. For the two-way link to European institutes, we installed an earth station at NMIJ for the PAS-4 satellite that is above the Indian sea. It will be available in very near future.

Two kinds of research activities are underway for highly precise time and frequency transfer. One of them is precise frequency transfer using an optical fiber network. We are developing a bi-directional fiber amplifier which can realize long distance frequency transfer using a single optical fiber. Preliminary results obtained in the laboratory using 100 km optical fiber show the system noise to be better than 9×10^{-16} for an averaging time of 10,000 s [8]. The other activity is basic research on the TWSTFT using carrier phase for sub pico-second level time transfer, and for $10^{-16} - 10^{-17}$ level frequency transfer.

6. Frequency calibration service

In January, 2005 frequency remote calibration service using GPS common-view method began, in addition to the in-house frequency calibration service [9]. Received data from the GPS common-view receivers at client sites is automatically transferred to the NMIJ data server everyday and monthly certifications are provided to the customers. We have seven customers including two Japanese-descended companies located at outside of Japan.

We are also studying the possibility of frequency dissemination using the clock signal of the public digital communication network. The preliminary results show the capability of frequency distribution to be 10^{-12} for the averaging time of 1 day [8].

7. Frequency measurement of Sr optical lattice clock

The Sr optical lattice clock was developed by the University of Tokyo, and NMIJ has collaborated to measure its absolute frequency. The university is about 50 km away from the NMIJ. The first measurement was carried out using a commercial Cs clock referenced to the SI second and the result was 429,228,004,229,952(15) Hz [10, 11]. Later JILA measured the frequency to be 429,228,004,229,869(19) Hz [12]. These two results have a poor agreement.

Recently, the University of Tokyo and NMIJ have performed an improved frequency measurement based on a hydrogen maser linked to UTC(NMIJ) using GPS

carrier phase signals [13]. The Allan standard deviation of the Sr lattice clock was found to reach 2×10^{-15} at an averaging time of 1300 s. The newly obtained absolute frequency of the Sr lattice clock was 429,228,004,229,875 Hz, with an uncertainty of 4 Hz. This frequency value differs from our previous measurement by five times the combined uncertainty but falls within the uncertainty of the JILA value. The preliminary results of our improved frequency measurement were presented at the CLEO/QELS 2006 conference [14]. Later it was learned that the SYRTE group has posted their measured frequency value of the Sr lattice clock as 429,228,004,229,879(5) Hz on the arXiv [15] during the CLEO/QELS conference. There is good agreement between the measurement results of the three groups.

8. Yb optical lattice clock

Development of an Yb optical lattice clock is in progress at NMIJ/AIST in cooperation with the University of Tokyo. The vacuum system, including the source oven, the Zeeman slower, and the magneto-optical trap (MOT) chamber have been constructed. The LD based 399 nm laser system for the Zeeman slower and the MOT has also been constructed. The violet MOT has been successfully built. The fiber laser based 556 nm SHG system for the spin-forbidden MOT, and the 578 nm SFG laser system for the 1S_0 - 3P_0 clock transition have been prepared.

9. Fiber frequency comb

A fiber-based frequency comb system has been developed. The system consists of a modified mode-locked fiber laser and a backward pumping amplifier, combined with a highly nonlinear fiber, which has a short zero-dispersion wavelength. As a result, the signal to noise ratio of the obtained carrier-envelope-offset frequency is larger than 45 dB at a bandwidth of 100 kHz. Using the fiber-based comb system, frequency measurements of a 1542-nm acetylene-stabilized laser and a 532-nm iodine-stabilized Nd:YAG laser were taken over a continuous period of more than one week. The long-term measurement revealed that the frequency stability of the iodine-stabilized laser was 5.7×10^{-15} at an averaging time of 100 000 s [16].

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