Progress of the fountain frequency standard at NMIJ in 2008

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***Abstract*—National Metrology Institute of Japan (NMIJ) is developing two fountain frequency standards (NMIJ-F1, NMIJ-F2). NMIJ-F1 is in the phase of operation for continuous monthly report since February in 2008. The possibility of the reduction in the uncertainty caused by the collisional shift that mainly limits the total uncertainty of NMIJ-F1 is presented. The construction of NMIJ-F2 proceeded, and then the launched atomic signal was observed.**

I. Introduction

Recently, the progress in the development of Cs atomic fountain primary frequency standard is highly significant. For these ten years, the systematic and the statistical uncertainty go down to a level below 10^{-15}. In the flame of International comparison, three fountains (NIST-F1, SYRTE-FO1, and SYRTE-FO2) agree at a level below $0.4\text{x}10^{-15}$[1]. For purpose of further confirmation of international correspondence, it is necessary that many different national labs join the level below $1.0\text{x}10^{-15}$.

Since the first operation of NMIJ-F1in 2005, we have performed frequency measurement using an atomic fountain frequency standard (NMIJ-F1) to calibrate International Atomic Time (TAI) a few times per year with an uncertainty of $3.9\text{x}10^{-15}$[2]. Although the uncertainty is not relatively small, the operational rate has recently been increased. The improvement of these operational rate is due to the modification of electronics and optics [2,3]. Stationary operation of NMIJ-F1 for continuous monthly reports has been almost performed since February 2008. At the same time, the construction of the second fountain (NMIJ-F2) has just begun [3]. We aim an uncertainty of the order of 10^{-16}, employing NMIJ-F1 in stationary operation as a reference oscillator. In this paper, we describe recent status of NMIJ-F1, and NMIJ-F2.

II. NMIJ-F1

We have started the frequency comparison with an uncertainty of $3.9\text{x}10^{-15}$ between TAI and NMIJ-F1 since 2005. So far, our data have been reported to the Bureau International des Poids et Measures (BIPM) for 17 times. Fig. 1 shows our activities after 2007. Since February in 2008 NMIJ-F1 is operated almost monthly. It might be general that the reduction of uncertainty should be tried: nevertheless we take priority of the improvement in the operationality of NMIJ-F1 due to the problem of our hydrogen maser stability. So, we are trying the uncertainty of 10^{-16} using NMIJ-F2 while solving the above problem using NMIJ-F1 as a local oscillator.

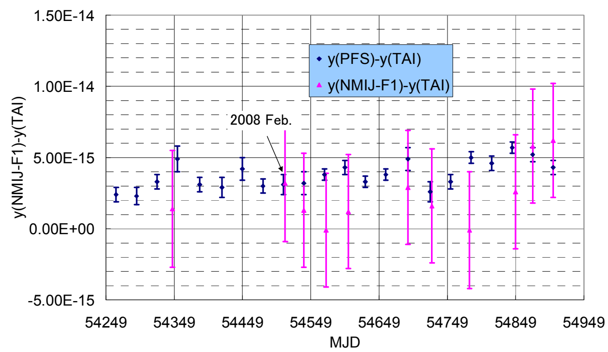

Fig 1. International comparisons between TAI and NMIJ-F1: Pink plot (blue plot) represents the frequency difference between NMIJ-F1(PFS) and TAI. The frequency of PFS is estimated by BIPM, considering all primary frequency standard joining to calibrate TAI.

For the meanwhile, the uncertainty of $3.9\text{x}10^{-15}$ in NMIJ-F1 consists mainly of that caused by the collisional frequency shift, which is $3.3\text{x}10^{-15}$. This frequency shift is dependent on the density of Cs atoms moving in parabolic. In order to estimate the uncertainty, the density dependent frequency shift should be investigated. After February in 2008, it was confirmed that the variation in the density of Cs atoms did not disturb the regular operation: (The frequency change measured against TAI is smaller than the uncertainty of $3.3\text{x}10^{-15}$. It is preliminary estimated to be below $1\text{x}10^{-15}$.) Consequently, measurement capability, when using alternative operation, of the collisional frequency shift is examined by analyzing the data acquired during MJD 54839-54949(2009 January- April), which is shown as Total deviation $\sigma(\tau)$ versus

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averaging time τ. It is found that averaging time over 30days allow us to estimate the collisional frequency shift with an uncertainty of $0.8x10^{-15}$. If the reduction of this uncertainty is successful, total uncertainty of NMIJ-F1 is expected to be $2.2x10^{-15}$.

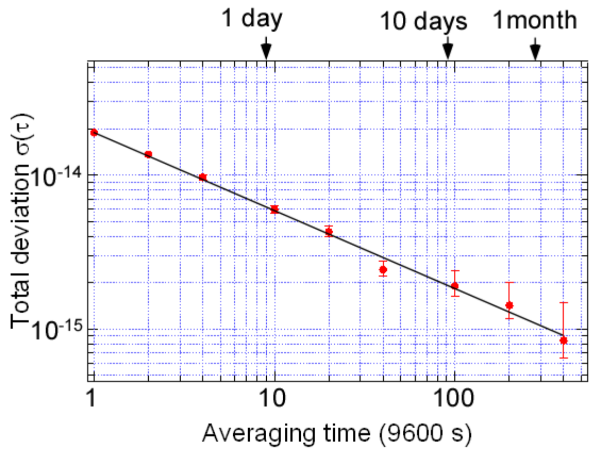

Fig. 2 Total deviation σ(τ) is calculated as a function of the averaging time τ. The cycle of alternative operation to vary the atomic density is assumed to 9600 s. σ(τ) of $1.3x10^{-12}$ $\tau^{-1/2}$ is drawn in a black line, which is corresponding to $9x10^{-13}$ $\tau^{-1/2}$ for a normal operation.

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III. NMIJ-F2

As to NMIJ-F2, we started assembling vacuum chambers and optical system last December. NMIJ-F2 is designed to have the higher frequency stability comparing with NMIJ-F1. For the purpose of that, (1,1,1) configuration (Fig. 3) to make molasses is employed so that more Cs atoms are involved in Ramsey interrogation. Detection region is prepared above the molasses area: Cs atoms after Ramsey interrogation do not pass accidentally where magnetic zero-cross point is located. An ion pump and a titanium sublimation pump vacuum inside physics package: the vacuum level reaches 10^{-7} Pa level without Cs gas, and 10^{-6} Pa with Cs gas. Two microwave cavities are sealed with ceramic windows: the time spent for bake out is shortened. The resonance frequency of microwave cavities are tuned to clock transition within the offset of 100 kHz at a room temperature that is stabilized to 23 ^{0}C. These microwave cavities and drift region are enclosed with three-layer magnetic shield having roughly 10,000 shielding factor.

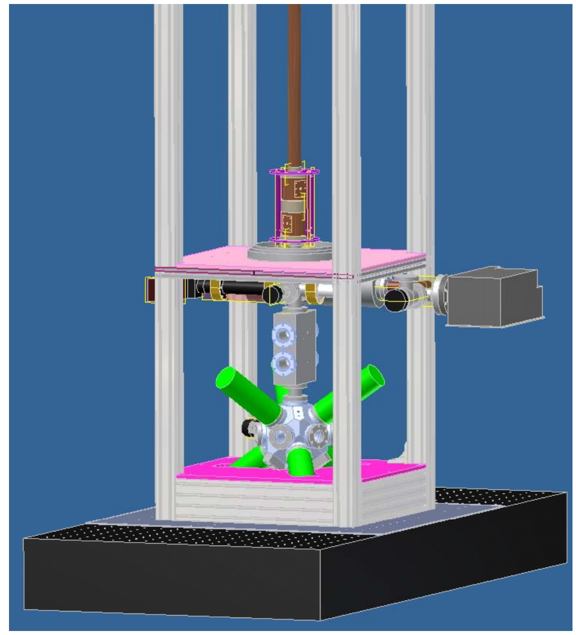

Fig. 3 Outline of main parts of physics package in NMIJ-F2

The basic concept of the optical system was already described in Ref. [3]. Three pairs of beam crossing all at right angle to make molasses are guided through the single-mode fibers near the physics package. Any beams are enlarged by beam expanders with a beam diameter of 24mm, and introduced to vacuum chamber. The laser detuning and intensity is controlled properly by timing pulse that is generated by pulse pattern generator. Cs atoms are experienced Doppler-cooling, moving molasses, and sub-Doppler cooling. Fig. 4 shows the atomic signal launched with 3m/s. Fig. 4 (a) and (b) shows fluorescence signals from Cs atoms moving upward and downward respectively. These signals are observed at 30cm over the molasses region. In general, atomic initial ball size σ_0, atomic ball size σ(t) as a function of t, RMS velocity V_{rms}, have the following relation:

$$\sigma(t)^2 = \sigma_0^2 + V_{rms}^2 t^2 \quad (1),$$

where t is the elapsed time after lunching. By using the equation (1), V_{rms} and σ_0 is calculated to be 8.6 cm/s and 8.8mm respectively. The RMS atom velocity translate into the thermal temperature T of 120 μK using the relation of $V_{rms}^2 = k_B T/m$, where m is the mass of a Cs atom and k_B is Boltzmann's constant. The cooled temperature is far from the recoil limit and is rather just below Doppler limit. This is most likely caused that stray magnetic field have an influence on the cooling process, and that the timing sequence for sub-Doppler cooling is not still optimized.

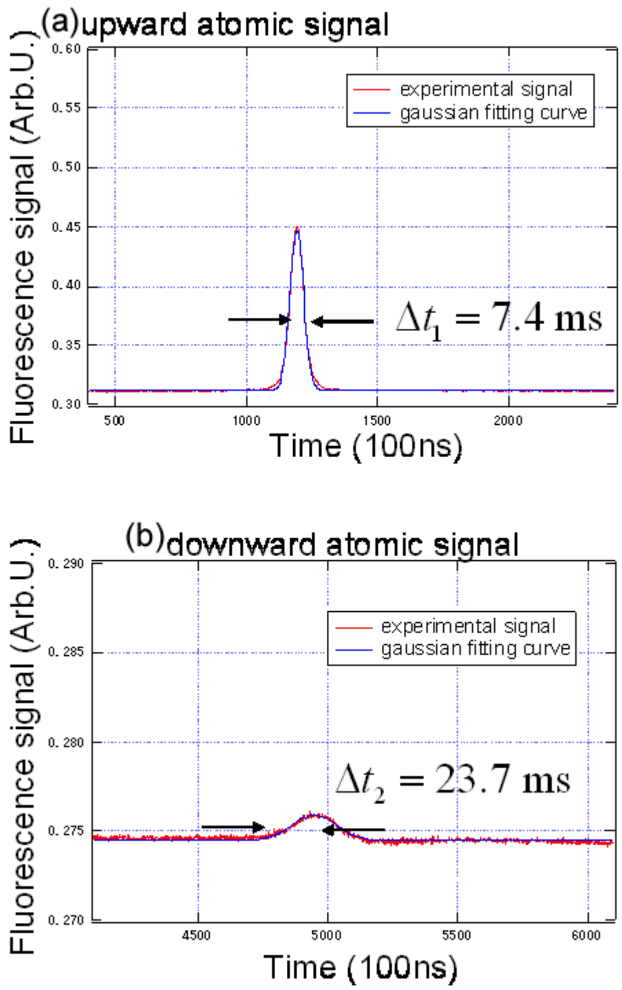

Fig. 4 Time-of-flight signal of (a) upward signal and (b) downward signal. Red lines represent the real-real time signal emitted from Cs atoms. Blue lines represent Gaussian fitting curve. A horizontal axis represents the elapsed time after launching. For (a) and (b) full widths at half maximums are estimated to be 7.4 ms and 23.7 ms respectively.

IV. CONCLUSION AND FUTURE PROSPECT

We reviewed the role of two frequency standards in the improvement of our activity, and reported the present status of our development in 2008.

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