Date: September, 10, 2005

Dear Dr.Arias, BIPM,

Attached is the first report on the frequency measurement by NMIJ-F1, a cesium atomic fountain frequency standard of NMIJ. Two measurements are reported and their measurement periods were ten days each. The measurement dates are **MJD 53549-53559** and **MJD 53589-53599**. The details of the uncertainty evaluation are described in the report.

Sincerely yours,

Takeshi Ikegami
Shinya Yanagimachi

National Metrology Institute of Japan (NMIJ) / National Institute of Advanced Industrial Science and Technology (AIST)
Time and Frequency Division
Time Standards Section
AIST Tsukuba Central 3, Tsukuba-Shi, Ibaraki-Ken 305-8563, Japan

Frequency comparison between H-Maser(405014) and Cs Fountain (NMIJ-F1) during **MJD 53549-53559** and **MJD 53589-53599**

National Metrology Institute of Japan(NMIJ) has measured the frequency of our Hydrogen maser HM (Clock # 405014) using the Cs atomic fountain frequency standard NMIJ-F1 during **MJD 53549-53559** and during **MJD 53589-53599**. The results are shown in Tables 1 and 2. Uncertainties are larger than the preliminary estimations Ref. [1, 2], because the present operational conditions are slightly different from those days. The conditions will be improved, and will approach to the best one in future.

Period	**53549-53559**
Measurement ratio	98.3 %
Y(NMIJ-F1)-Y(Maser 405014)	37.1
u_A	1.1
u_B	3.8
$u_{link\ /\ lab}$	0.5

Table 1. Results of the comparison in 1x10^{-15} unit.

Period	**53589-53599**
Measurement ratio	93.5 %
Y(NMIJ-F1)-Y(Maser 405014)	100.2
u_A	1.1
u_B	4.0
$u_{link\ /\ lab}$	0.5

Table 2. Results of the comparison in 1x10^{-15} unit.

The uncertainty budgets of NMIJ-F1 in the two measurements are shown in Tables 3 and 4. The estimation procedures are described in Ref [1-4].

Source of uncertainty	Bias	Uncertainty
2nd order Zeeman	185.2	0.7
Blackbody radiation	-18.0	1.4
Gravitation	1.6	0.1
Cold collisions	0.0	3.3
Distributed cavity phase	-	1.2
Total	168.8	3.8

Table 3. Frequency biases and uncertainties in NMIJ-F1 during the period **MJD 53549-53559** in 1×10^{-15} unit.

Source of uncertainty	Bias	Uncertainty
2nd 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

Table 4. Frequency biases and uncertainties in NMIJ-F1 during the period **MJD 53589-53599** in 1×10^{-15} unit.

The uncertainties u_A, $u_{link/lab}$, u_B are described in the following briefly.

1. 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 $1\times10^{-12}\,\tau^{-1/2}$. Assuming white FM noise over the comparison period, the measurement uncertainty based on the frequency instability is 1.1×10^{-15} for 10 days.

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

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

$$u_{link/lab} = \sqrt{u_{dead\ time}{}^2 + u_{link/maser}{}^2}, \qquad (1)$$

where $u_{link/maser}$ is the uncertainty due to the noise of the phase comparator between the fountain and HM, $u_{dead\ time}$ is the uncertainty due to the operational dead time of the fountain. NMIJ-F1 was operated almost continuously and its efficiencies were 98.3 % during **MJD 53549-53559** and 93.5 % during **MJD 53589-53599** respectively. The operation was only interrupted sometimes due to earthquakes, electric power failures and so on, and $u_{dead\ time}$ in the two measurements were 1×10^{-16} during **MJD 53549-53559**, and 2×10^{-16} during **MJD 53589-53599** respectively. The resulting uncertainty contributing to $u_{link/lab}$ is shown in Tables 5 and 6.

	Uncertainty
$u_{link/maser}$	0.5
$u_{dead\ time}$	0.1

Table 5. Uncertainty is expressed in 1×10^{-15} unit during **MJD 53549-53559**

	Uncertainty
$u_{link/maser}$	0.5
$u_{dead\ time}$	0.2

Table 6. Uncertainty is expressed in 1×10^{-15} unit during **MJD 53589-53599**

3. Type B uncertainty u_B

A. 2nd order Zeeman shift

Using the linear Zeeman shift of the |F=3, m=-1> → |F=4, m=-1> transition, frequency bias induced by the quadratic Zeeman shift of the clock transition is estimated from the following equation,

$$\Delta\nu_{quadratic\_Zeeman} = \frac{8\left(\delta\nu_{linear\_Zeeman}\right)^2}{\nu_0}, \qquad (2)$$

where $\Delta\nu_{quadratic\_Zeeman}$ is the relative frequency shift, and ν_0 is the resonance frequency of clock transition. The details of the approach to estimate uncertainty of the quadratic Zeeman shift is described in Ref. [3]

B. Black body radiation

The temperature of the drift region was estimated from the measurement with a platinum thermometer attached to the vacuum chamber and the measurement of the resonance frequency on the microwave cavity that has a temperature coefficient of 150 kHz/°C. The black body radiation shift is estimated using the following equation.

$$\Delta\nu_{BBR} = -1.711\times10^{-14}\times\left(\frac{T}{300}\right)^4\left[1+0.014\times\left(\frac{T}{300}\right)^2\right] \qquad (3)$$

The frequency biases and uncertainties due to the black body radiation in the two measurements (**MJD 53549-53559** and **MJD 53549-53559**) were different, because we slightly changed the temperature of the vacuum chamber.

C. Gravitational red shift

The microwave cavity is located at a height of 14.3 ± 0.5 m above sea level. The gravitational red shift is estimated using the following equation.

$$\Delta\nu_{RS} = 1.09\times10^{-16}\times h \qquad (4)$$

D. Cold collisions

NMIJ-F1 was operated using a low density optical molasses for the present measurements. In the optical molasses configuration, a smaller collisional frequency shift is expected than that in the MOT configuration that was used for the estimation of the collisional frequency shift of $(2.7 \pm 0.6) \times 10^{-15}$ [2]. We consider the value of $3.3 \times 10^{-15} = (2.7 + 0.6) \times 10^{-15}$ as the uncertainty for the moment, and 0 as the frequency bias. Actually, we operated in different number of atoms with the molasses configuration, but a significant frequency change depending on the number of atoms was not observed. The resolution of its observation is currently limited by the frequency stability of NMIJ-F1, then we need longer accumulation time to estimate the collisional frequency shift more precisely. That is remained as our future subject.

F. Distributed cavity phase

The microwave cavity used in NMIJ-F1 has two ports to couple with the oscillated magnetic field from a local oscillator. Presently a single port is used to introduce the oscillated magnetic field. In this configuration, the uncertainty due to the distributed cavity phase shift is estimated to be 1.2×10^{-15}. The method to determine this uncertainty is described in Ref. [4].

References

[1] Takayuki Kurosu, Yasuhiro Fukuyama, Yasuki Koga and Kentaro Abe, “Preliminary evaluation of the Cs atomic fountain frequency standard at NMIJ/AIST.” IEEE Trans. Instrum. Meas., vol. 53, pp. 466-471, 2004

[2] T. Kurosu, Y. Fukuyama, K. Abe, S. Yanagimachi and Y. Koga, “Evaluation of the Cs atomic fountain frequency standard at NMIJ/AIST.” Proceedings of the joint meeting EFTF/FCS, Tampa, May 2003. pp. 68-71.

[3] Takayuki Kurosu, Yasuhiro Fukuyama, Kentaro Abe and Yasuki Koga, “Measurement of a Weak magnetic field using cold atoms.” Jpn. J. Appl. Phys. 41, pp. L586-588, 2002.

[4] S. Yanagimachi, Y. Fukuyama, T. Ikegami and T. Kurosu, "Numerical Simulation of Distributed Cavity Phase Shift in Atomic Fountain Standard." Jpn. J. Appl. Phys. 44, pp. 1468-1475, 2005.