Date: September, 30, 2006

Dear Dr. Arias, BIPM,

Attached is the report on the frequency measurement by NMIJ-F1, a cesium atomic fountain frequency standard of NMIJ, during **MJD 53974-53984**. A basic performance and uncertainty of NMIJ-F1 are almost the same as those in the last publication. The details of the present configuration or a history in the modification are described in Refs. [1-5].

In order to have better reliability and operationality of NMIJ-F1, some parts of both hardware and software have been upgraded. 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. By using this new pulse pattern generator, parameters such as launch height, sequence cycle in the fountain, and shutter timing, are easily adjustable. Inner/outer type DC blocks have been inserted between microwave synthesizers and cavities to eliminate possible ground loop effect. Those modifications will leads to reduce the uncertainty of NMIJ-F1 in the future. In the present report, the uncertainty contributed by microwave power dependence is added to the uncertainty budget. The details of this evaluation are included in the present report.

Before submitting the present report of TAI calibration, we investigated the effect of these modifications on the frequency behavior in NMIJ-F1 during two and a half months. We could confirm the improvement of long-term stability with the above modifications. These informal data are appended as supplementations.

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Frequency comparison between H-Maser(405014) and Cs Fountain(NMIJ-F1) during MJD 53974-53984

The frequency of our Hydrogen maser HM(Clock # 405014) have been measured using NMIJ-F1 during MJD 53974-53984. The results are shown in Table 1.

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

Period	**53974-53984**
Measurement ratio	89.8 %
Y(NMIJ-F1)-Y(Maser 405014)	-36.6
u_A	1.1
u_B	3.9
$u_{link / lab}$	0.6

1. Type A uncertainty u_A

The value of type A uncertainty u_A is not changed.

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

The uncertainty of the link in the laboratory, $u_{link / lab}$, is written as,

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

where $u_{link / maser}$ is the uncertainty due to the phase noise of the synthesis chain between the fountain and HM, $u_{dead\ time}$ is the uncertainty due to the operational dead time of the fountain. $u_{link / maser}$ and $u_{dead\ time}$ are evaluated to be 5×10^{-16}, 3×10^{-16} respectively.

3. Type B uncertainty u_B

3-1. 2nd order Zeeman shift

Using the linear Zeeman shift of the |F=3, m=1> → |F=4, m=1> transition, the frequency bias and the uncertainty which are induced by the quadratic Zeeman shift of the clock transition is determined. Figure 1 shows a spatial inhomogeneity of the magnetic field as a function of launched height, which is checked every month. Such a spatial inhomogeneity gives the uncertainty less than 10^{-17}. On the other hand, the temporal variation of this magnetic sensitive transition is observed to be smaller than 1.6 Hz, which limits dominantly the uncertainty induced by the quadratic Zeeman shift. The resulting uncertainty is conservatively determined to be 5×10^{-16}.

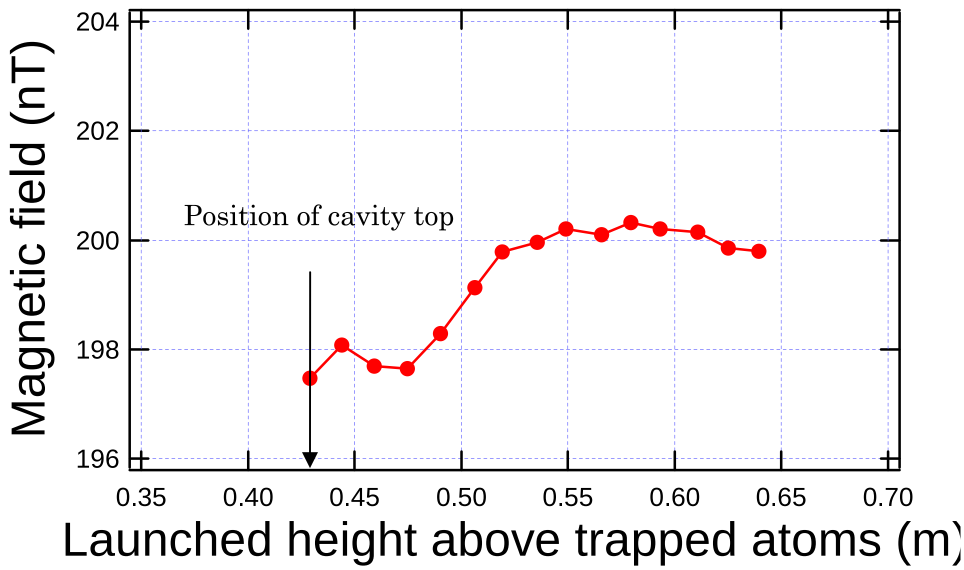

Figure 1: Map of the magnetic field in NMIJ-F1

3-2. Black body radiation

The bias or the uncertainty induced by the Black body radiation is estimated from the following equation.

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

The resulting uncertainty is 1.4×10^{-15}, which is caused by a spatial variation of the drift tube in temperature. The temperature is slightly modified from the last publication (MJD 53629-53639).

3-3. Microwave power dependence

Recently, the frequency shift which depends on the microwave power was investigated in NMIJ-F1. The experimental results shown in figure 2 were taken under an "alternating operation" in the microwave power. The frequency difference is observed for the pulse area of $\frac{2n+1}{2}\pi \ \ (n=1,2,3,4,5)$, using the frequency for the pulse area of $\frac{\pi}{2}$ as a reference.

The power dependence is described in the formula as

$$f(p) = c_1 p + c_2\sqrt{p}\sin\left(\sqrt{p}\frac{\pi}{2}\right), \qquad (3)$$

where c_1 and c_2 are fitting parameters, and p is scaled in an optimum microwave power corresponding to $\frac{\pi}{2}$ pulse area that is used for a normal operation [6]. This function is based on the theoretical and experimental findings of PTB's group [7]. Our purpose is to determine a frequency shift for the normal operation, which is calculated by Eq. (3) for $p=1$,

$$f\left(p=1\right)=c_1+c_2. \tag{4}$$

So, the fitting function, $F\left(p\right)$, to the experimental data taken under the alternating operation is derived as

$$\begin{aligned} F\left(p\right) &= f\left(p\right)-f\left(p=1\right) \\ &= c_1\left(p-1\right)+c_2\left(\sqrt{p}\sin\left(\sqrt{p}\frac{\pi}{2}\right)-1\right) \end{aligned}, \tag{5}$$

using Eqs. (3) and (4). A least square fit provides $c_1=\left(0.3\pm0.3\right)\times10^{-16}$ and $c_2=\left(-4.5\pm2.3\right)\times10^{-16}$. Using these two obtained value, the possible frequency shift is estimated to be $\left(-4.2\pm2.3\right)\times10^{-16}$, where the maximum of the absolute value having a confience interval is 6.5×10^{-16}. For this consideration, we set 0 as the frequency bias, and 7×10^{-16} as the uncertainty, which are determined conservatively.

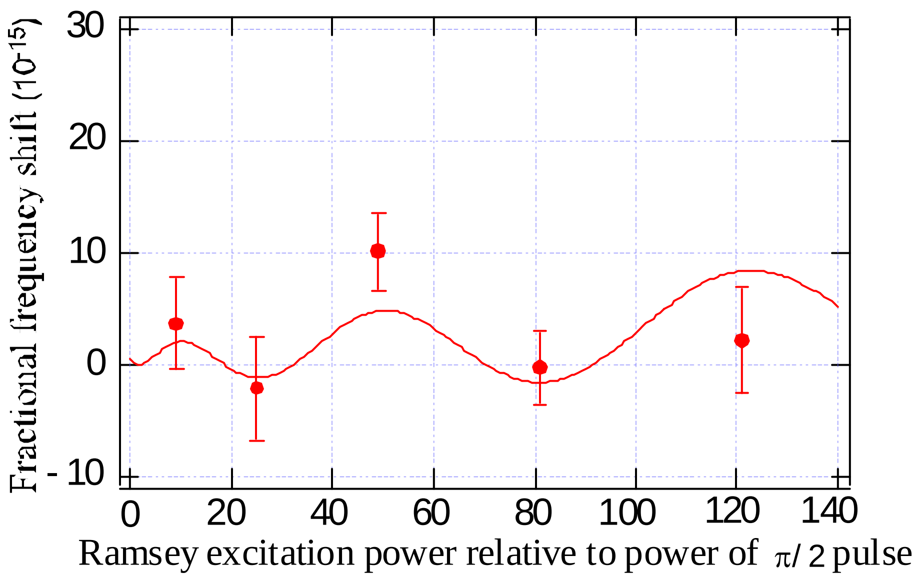

Figure 2: Power dependence of the frequency in NMIJ-F1

3-3. Summary of Type B uncertainty

Table 2 shows the frequency biases and uncertainties for the present report. Although the uncertainty contributed by the microwave power dependence is newly added as the value of 10^{-16} order, it hardly has an influence on the overall type B uncertainty. The uncertainty induced by the cold collision frequency shift dominantly contributes the overall type B uncertainty. The modification of parts related to electronics at this time gives us a prospect to reduce the uncertainty induced by the cold collision frequency shift.

Table 2: Frequency biases and uncertainties in NMIJ-F1 during the period **MJD 53974-53984**. in 1×10^{-15} unit.

Source of uncertainty	Bias	Uncertainty
2nd order Zeeman	185.0	0.5
Blackbody radiation	-18.0	1.4
Gravitation	1.6	0.1
Cold collisions	0.0	3.3
Distributed cavity phase	0.0	1.2
Microwave power dependence	0.0	0.7
Total	168.6	3.9

[1] S. Yanagimachi, K. Watabe, K. Hagimoto, A. Kubota, T. Ikegami, and S. Ohshima, "Recent status of an atomic fountain frequency standard at NMIJ(NMIJ-F1)", to be published in Proc. 2006 of EFTF

[2] 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

[3] 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.

[4] 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.

[5] 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.

[6] K. Szymaniec, W. Chalupczak, P. B. Whibberley, S. N. Lea, and D. Henderson,

" Reply to the comment on 'Evaluation of the primary frequency standard NPL-CsF1' ", Metrologia **43**, L18–L19 (2006)
[7] S. Weyers, R. Schröder, R. Wynands, "Effects of microwave leakage in caesium clocks: theoretical and experimental results", to be published in Proc. 2006 of EFTF

Supplement data in NMIJ-F1 during MJD 53904-53974

Data shown in the table 3 are additional information that could calibrate TAI during the period of MJD 53904-53974. The measured frequency of Hydrogen maser(Clock # 405014) is averaged for 10 days. The measurement ratio for MJD 53924-53964 was smaller than the other period, because NMIJ-F1 was operated for the investigation of the microwave power dependence. Y(PFS-NMIJ_F1), the last column of this table, represents the fractional frequency difference between PFS and NMIJ-F1, where PFS is the scale unit estimated by BIPM using submitted data of primary frequency standards.

Figure 3 shows a plot of Y(PFS-NMIJ_F1) with the error bar indicating the combined uncertainty (including $u_{link / TAI}$). Consequently, we could confirm that some modifications performed at this time have no effect on the frequency of NMIJ-F1

Table 3: Informal data (1x10^{-15} unit) collected before the present report of NMIJ-F1

Period	Measurement ratio	Y(NMIJ_F1-Maser 405014)	u_A	u_B	$u_{link / lab}$	Y(PFS-NMIJ_F1)
53904-53914	84.7 %	-21.5	1.1	3.9	0.6	-4.9
53914-53924	90.6%	-17.4	1.1	3.9	0.6	-5.4
53924-53934	44.3%	-23.2	1.1	3.9	1.0	-1.0
53934-53944	48.7%	-23.5	1.1	3.9	0.9	4.9
53944-53954	49.4%	-22.9	1.1	3.9	0.9	-3.7
53954-53964	61.8%	-35.5	1.1	3.9	0.8	0.5
53964-53974	85.6%	-34.0	1.1	3.9	0.6	-0.2

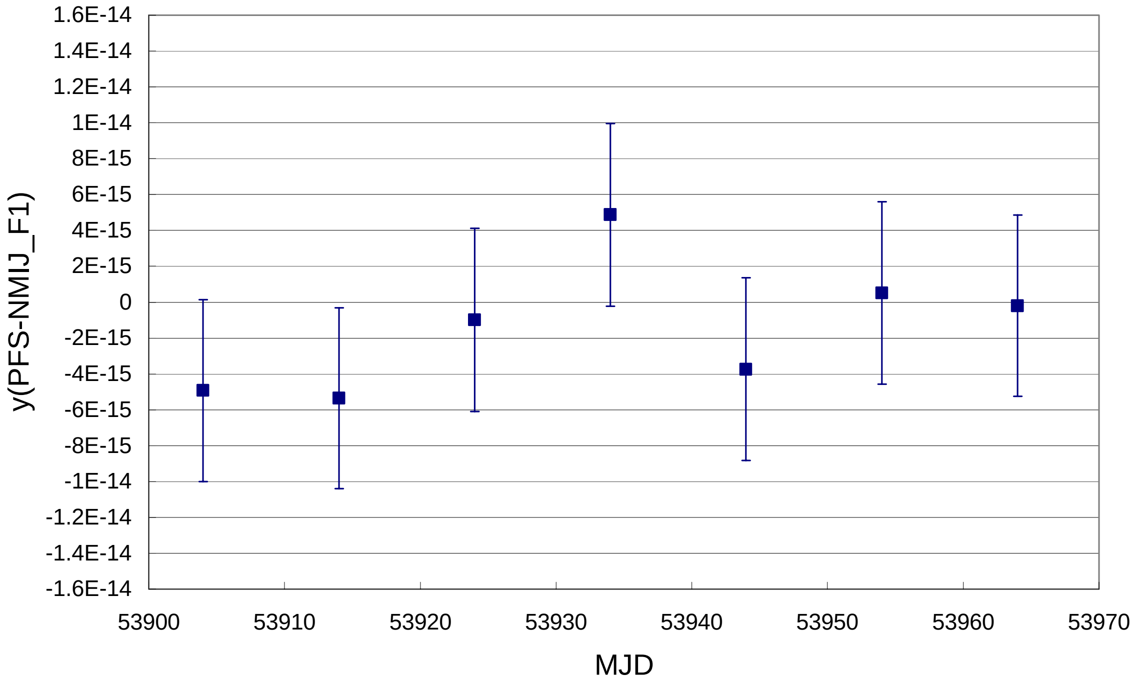

Figure 3: Informal data of Y(PFS-NMIJ_F1)