Frequency comparison between the hydrogen maser (1405003) and Cs fountain primary frequency standard NMIJ-F2 for the period MJD 59219-59244

The fractional frequency difference between the hydrogen maser (HM) (clock number: 1405003) and the Cs fountain primary frequency standard NMIJ-F2, $y(\mathrm{HM} - \mathrm{NMIJF2})$, has been measured for the period between MJD 59219 and MJD 59244. The result is summarized in table 1. The details of the operation and uncertainty evaluation of NMIJ-F2 are described in reference [1].

Table 1. The result of the frequency comparison.

Period	MJD 59219 - 59244
Intermediate local reference	HM (1405003)
$y(\mathrm{HM} - \mathrm{NMIJF2})$	-83.84×10^{-15}
u_A	0.19×10^{-15}
u_B	0.46×10^{-15}
$u_\mathrm{A/Lab}$	0.24×10^{-15}
$u_\mathrm{B/Lab}$	0.00×10^{-15}
Fractional uptime	85.1 %

(1) Frequency difference $y(\mathrm{HM} - \mathrm{NMIJF2})$

According to the guidelines for reporting data [2], $y(\mathrm{HM} - \mathrm{NMIJF2})$ for the measurement period was obtained as the value at the middle of the period using a linear fit. The frequency data were averaged over 1 day intervals. Then, the fitting to the values of $y(\mathrm{HM} - \mathrm{NMIJF2})$ was performed by a least-square method with weights given from the numbers of the data in a day.

(2) Type A uncertainty (u_A)

The number of atoms involved in the Ramsey interrogation was alternated between the large and small numbers to correct the collisional shift. The frequency extrapolated to zero density was obtained every 50 fountain sequences (82.5 s). The frequency stability of NMIJ-F2 at zero density was evaluated from the overlapping Allan deviation, where the local oscillator, the cryogenic sapphire oscillator loosely locked to the HM with a time constant of 300 s, was used as a reference. The frequency stability was $2.6 \times 10^{-13}(\tau/\mathrm{s})^{-1/2}$, where τ is the averaging time. Substituting the uptime 21.3 d into τ, it was obtained that $u_\mathrm{A} = 1.9 \times 10^{-16}$.

(3) Type B uncertainty (u_B)

Table 2 shows the budget for the fractional frequency corrections and type B uncertainty at a low density. Only the frequency corrections for the second-order Zeeman effect and blackbody radiation shift were evaluated for this measurement period. The uncertainty for the blackbody radiation shift was slightly reduced from reference [1] due to replacement of the coefficient as described below. The frequency correction for the gravitational shift was slightly changed from reference [1] with reductio of the uncertainty as described below. The other frequency corrections and uncertainty were taken from reference [1].

Table 2. Uncertainty budget of NMIJ-F2.

Effect	**Correction/10^{-16}**	**Uncertainty/10^{-16}**
Second-order Zeeman	−1726.6	0.6
Blackbody radiation	+168.0	0.7
Collisional shift	+31.6	0.3
Distributed cavity phase	0	3.4
Lensing	0	0.9
Microwave leakage	−1.2	2.5
Background gas pressure	0	1.0
Gravity	−16.8	0.1
Light shift	0	< 0.01
Rabi, Ramsey pulling	0	0.4
Cavity pulling	0	0.9
Spurious	0	0.2
Total	−1545.0	4.6

The second-order Zeeman effect was evaluated by taking Ramsey fringes for $m_F = +1$ for different launch heights in increments of a few centimeters. Using them, the frequency shift due to the second-order Zeeman effect for $m_F = 0$ in the normal operation was calculated. The measurements were performed at MJD 59222 and 59248 for the beginning and end of the frequency measurement period, respectively. The average of the two values was used for the frequency correction.

The blackbody radiation shift was evaluated by measuring the temperature of the middle of the drift tube. The frequency correction was calculated from the temperature averaged over the uptime. Here, the temperature of the vacuum chamber was stabilized by the room temperature using an air conditioner. Here, we replaced the value of the coefficient $\beta = (-1.710 \pm 0.006) \times 10^{-14}$ [3], which was used in our evaluation paper [1], with $\beta = (-1.718 \pm 0.003) \times 10^{-14}$ [4]. This replacement varied the frequency correction for blackbody radiation by $+0.8 \times 10^{-16}$, and its uncertainty is reduced from 0.9×10^{-16} to 0.7×10^{-16}.

For the gravitational shift, we used the gravitational potential of NMIJ-Yb1, W_{Yb1} = 62 636 648.59 ± 0.50 $\mathrm{m}^2\ \mathrm{s}^{-2}$ [5]. The frequency correction for the gravitational shift was evaluated to be $(W_{\mathrm{Yb1}} - gh_{\mathrm{F2}} - W_0)/c^2$, using the average height of atoms over the interrogation time at NMIJ-F2 from the optical lattice of NMIJ-Yb1, $h_{\mathrm{F2}} = -5.69 \pm 0.10$ m. Here, g and c are the gravitational acceleration and the speed of light, respectively. The gravitational potential for TT/TAI, W_0 = 62 636 856.0 $\mathrm{m}^2\ \mathrm{s}^{-2}$. The frequency correction and uncertainty for the gravitational shift were changed from $(-16.7 \pm 0.6) \times 10^{-16}$ described in reference [1] to $(-16.8 \pm 0.1) \times 10^{-16}$.

(4) Uncertainty in the link between UTC(NMIJ) and NMIJ-F2 ($u_{\mathrm{A/Lab}}$, $u_{\mathrm{B/Lab}}$)

The uncertainty $u_{\mathrm{A/Lab}}$ consisted of the uncertainty due to the deadtime, the uncertainty of the time interval counter to obtain the data of x(UTC(NMIJ) – HM) for the monthly reports to BIPM, and the uncertainty of the phase noise in the cables connecting between HM and NMIJ-F2 located in the different rooms.

To evaluate the deadtime uncertainty, the frequency of the HM was considered with a numerical simulation. A programing software generated n random numbers for a measurement period of n s based on the noise properties of the HM. The ith number corresponded to the frequency of the HM at time $t = i$ s. Here, the HM was assumed to have a white phase noise; 4.7×10^{-13}, a white frequency noise; 7.3×10^{-14}, a flicker floor noise; 1.5×10^{-15}, a random walk noise; 9×10^{-19}, and a frequency drift; 3×10^{-22} at 1 s. To evaluate the frequency of the HM in the entire period including the deadtime of the fountain, all the n numbers were averaged. On the other hand, to evaluate the frequency of the HM in the period except the deadtime, the numbers except the ones corresponding to the deadtime were averaged. The difference between the two averaged numbers gave the difference between the average of the HM frequencies over the entire period and the one over the period except the deadtime. This process was repeated 1000 times, and the deadtime uncertainty was evaluated at 1.8×10^{-16} from the square root of the quadratic sum of the mean and standard deviation of the differences.

In addition, y(UTC(NMIJ) – HM) was measured near NMIJ-F2 by a phase meter with a dualmixer time difference measurement system and compared with y(UTC(NMIJ) – HM) measured near the HM by the time interval counter for one month. The difference between the two y(UTC(NMIJ) – HM) came from both the measurement noise of the time interval counter and the phase noise in the cables. The uncertainty was evaluated at 1.6×10^{-16} by the square root of the quadratic sum of the mean and standard deviation. Combined with the deadtime uncertainty, $u_{\mathrm{A/Lab}}$ was given as 2.4×10^{-16}. On the other hand, we took that $u_{\mathrm{B/Lab}} = 0$.

[1] A. Takamizawa, S. Yanagimachi, and K. Hagimoto, 2022 *Metrologia* **59** 035004, https://doi.org/10.1088/1681-7575/ac5e7b.

[2] *Guidelines for reporting primary (PFS) or secondary (SFS) frequency standards data for TAI calibration,* available at https://webtai.bipm.org/database/guidelines.html.

[3] K. Beloy, U. I. Safronova, and A. Derevianko, 2006 *Phys. Rev. Lett.* **97** 040801, https://doi.org/10.1103/PhysRevLett.97.040801.

[4] P. Rosenbusch, S. Zhang, and A. Clairon, 2007 *Proc. European Frequency and Time Forum*, pp. 1060 – 1063.

[5] M. Nakashima, S. Fukaya, T. Toyofuku, K. Ochi, and K. Matsuo, 2022 *Proc. Japan Geoscience Union Meeting*, SGD02-14.