Frequency evaluation of UTC(NMIJ) by NMIJ-Yb1 for the period MJD 59424 to MJD 59454

The secondary frequency standard NMIJ-Yb1 has been compared to UTC(NMIJ), during a measurement campaign between MJD 59424 and MJD 59454 (29th July 2021 – 28th August 2021). The Yb optical lattice clock operation covers 94.5 % of the total measurement period.

1. Results

Table 1. (a) Results of the comparison in 1×10^{-16}

Period (MJD)	***y*(UTC(NMIJ) – NMIJ-Yb1)**	**Total u_A**	**Total u_B**	**$u_{A/Lab}$**	**$u_{B/Lab}$**	**u_{SecRep}**	**Uptime (%)**
59424 - 59454	-30.4	0.06	1.26	0.4	1.0	5	94.5

(b) Budget of uncertainties in 1×10^{-16}

u_A : Type A uncertainty	
Yb statistics	0.06
Total	0.06
u_B : Type B uncertainty	
Yb systematics	1.11
Gravitational	0.6
Total	1.26
$u_{A/Lab}$: Type A uncertainty	
Dead time in UTC(NMIJ) – Yb	0.4
Total	0.4
$u_{B/Lab}$: Type B uncertainty	
Microwave-optical frequency link	1.0
Total	1.0

The calibration is made using the most recently recommended value for the $6s^2\ {}^1S_0 - 6s6p\ {}^3P_0$ unperturbed optical transition in the ^{171}Yb neutral atom: 518 295 836 590 863.6 Hz [1]. u_{SecRep} is the recommended uncertainty of the secondary representation [1]

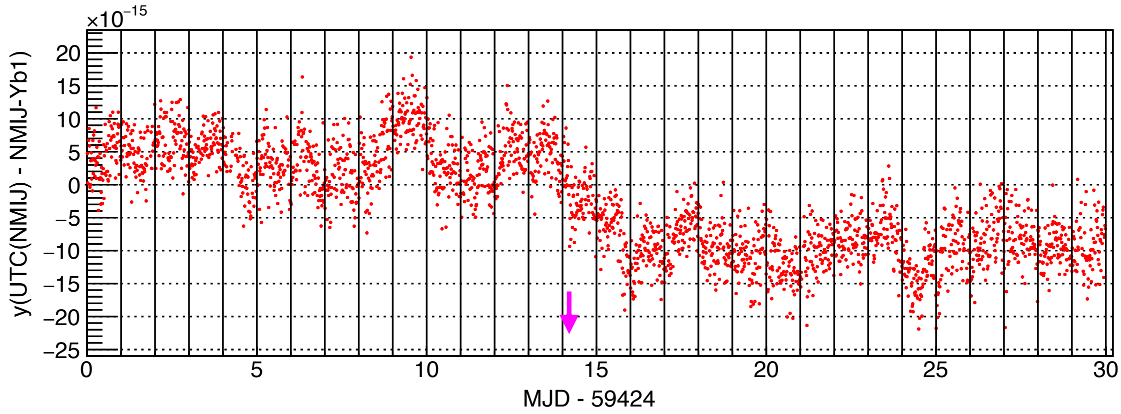

Figure 1. Data points of y(UTC(NMIJ) – NMIJ-Yb1) averaged over 10^3 s. The vertical arrow indicates the timing and polarity of the frequency steering of UTC(NMIJ), which is typically carried out by 5×10^{-15}.

2. Systematic effects and uncertainties

Table 2. Budget of systematic effects and uncertainties for NMIJ-Yb1 [2,3] in 1×10^{-17}

Effect	**Shift**	**Uncertainty**
Lattice light	3.6	5.6
Blackbody radiation	-249.9	8.7
Density	-2.1	1.1
Second order Zeeman	-5.1	0.3
Probe light	0.4	0.2
Servo error	-3.3	3.3
AOM switching	-	1
Line pulling	-	1
Total	-256.3	11.1
Gravitational redshift	229.4	6
Total (with gravitational redshift)	-26.9	12.6

For the reports submitted in November and December 2020, the total systematic uncertainty of NMIJ-Yb1 was improved to 2×10^{-16} compared with an uncertainty of 4×10^{-16} described in previous reports and Ref. [3]. A major improvement was made in the uncertainty of the lattice light shift ($3\times10^{-16}\rightarrow5\times10^{-17}$). Here we reduced the uncertainty of the magic frequency by a factor of ~1/3, and operated NMIJ-Yb1 with a lower trap potential depth of ~200*E*r, where *E*r denotes the recoil energy from a lattice photon.

For the reports submitted in August 2021, the total systematic uncertainty of NMIJ-Yb1 was improved to 1×10^{-16}. The uncertainty of the blackbody radiation shift was reduced from 2×10^{-16} to 9×10^{-17} by (a) improving the temperature inhomogeneity of a vacuum chamber for trapping atoms, (b) inserting an aperture to reduce the solid angle of a window heated at ~200 ℃, and (c) reevaluating the contributions from hot vacuum components (e.g., the heated window and atomic oven) with a Monte Carlo ray-tracing analysis.

The gravitational redshift was calculated with respect to the conventionally adopted reference potential W_0 = 62 636 856.0 m^2/s^2.

3. Frequency comparison

Table 3. Frequency correction and uncertainty for y(UTC(NMIJ) – NMIJ-Yb1) due to the dead time in UTC(NMIJ) – Yb in 1×10^{-17}

Effect	**Correction**	**Uncertainty**
Maser noise model	-	4.1
Steering	0.66	0.01
Total	0.7	4.1

The frequency of NMIJ-Yb1 was compared with UTC(NMIJ) using an optical frequency comb. A beat frequency between a laser locked to an ultra-stable cavity and the comb was counted. The frequency of the ultra-stable laser was shifted by an acousto-optic modulator (AOM) and stabilized to the clock transition in ^{171}Yb atoms trapped in an optical lattice. The frequency of the AOM was then combined with the beat frequency to compute y(UTC(NMIJ) – NMIJ-Yb1).

The uncertainty $u_{B/Lab}$ arose from a microwave-optical frequency link. For the reports submitted in November 2020 and after that, this uncertainty was improved to 1.0×10^{-16} compared with an uncertainty of 2.2×10^{-16} described in previous reports and Ref. [3]. The previous uncertainty was mainly caused by frequency multiplication of a 10 MHz signal from UTC(NMIJ). Here we reduced this uncertainty to low 10^{-17} by carefully stabilizing the temperature of a frequency multiplier. The present $u_{B/Lab}$ uncertainty was limited by phase variations of the 10 MHz signal that occurred during its transmission through a coaxial cable.

The uncertainty $u_{A/Lab}$ arose from the dead time in the comparison between NMIJ-Yb1 and UTC(NMIJ). This uncertainty was estimated using a method described in Ref. [4]. For this estimation, we derived a maser noise model from the measured stability of UTC(NMIJ) against NMIJ-Yb1. The model includes a white phase modulation of $1 \times 10^{-12} / (\tau /s)$, a white frequency modulation (FM) of $9 \times 10^{-14} / (\tau /s)^{1/2}$, a flicker FM of 2×10^{-15}, a random walk FM of 4×10^{-24}

$(\tau/\mathrm{s})^{1/2}$. $u_{\mathrm{A/Lab}}$ also includes the uncertainty of a frequency correction resulting from the dead time when the frequency steering of UTC(NMIJ) is carried out.

References

[1] "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the definition of the second," BIPM publication, approved by CCTF June 2017, https://www.bipm.org/utils/common/pdf/mep/171Yb_518THz_2018.pdf

[2] T. Kobayashi, D. Akamatsu, Y. Hisai, T. Tanabe, H. Inaba, T. Suzuyama, F.-L. Hong, K. Hosaka, and M. Yasuda, "Uncertainty Evaluation of an ^{171}Yb Optical Lattice Clock at NMIJ," IEEE Trans. Ultrason., Ferroelectr., Freq. Control **65**, 2449-2458 (2018).

[3] T. Kobayashi, D. Akamatsu, K. Hosaka, Y. Hisai, M. Wada, H. Inaba, T. Suzuyama, F.-L. Hong, and M. Yasuda, "Demonstration of the nearly continuous operation of an ^{171}Yb optical lattice clock for half a year," Metrologia **57**, 065021 (2020).

[4] D.-H. Yu, M. Weiss, and T. E. Parker, "Uncertainty of a frequency comparison with distributed dead time and measurement interval offset," Metrologia **44**, 91-96 (2007).