Frequency evaluation of UTC(NMIJ) by NMIJ-Yb1 for the period MJD 59819 to MJD 59844

The secondary frequency standard NMIJ-Yb1 has been compared to UTC(NMIJ), during a measurement campaign between MJD 59819 and MJD 59844 (28th August 2022 – 22nd September 2022). The Yb optical lattice clock operation covers 86.8 % 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 (%)**
59819 - 59844	-24.0	0.07	1.12	2.2	1.0	1.9	86.8

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

u_A : Type A uncertainty	
Yb statistics	0.07
Total	0.07
u_B : Type B uncertainty	
Yb systematics	1.12
Gravitational	0.06
Total	1.12
$u_{A/Lab}$: Type A uncertainty	
Dead time in UTC(NMIJ) – Yb	2.2
Total	2.2
$u_{B/Lab}$: 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: 518 295 836 590 863.63 Hz [1]. u_{SecRep} is the recommended uncertainty of the secondary representation [1]

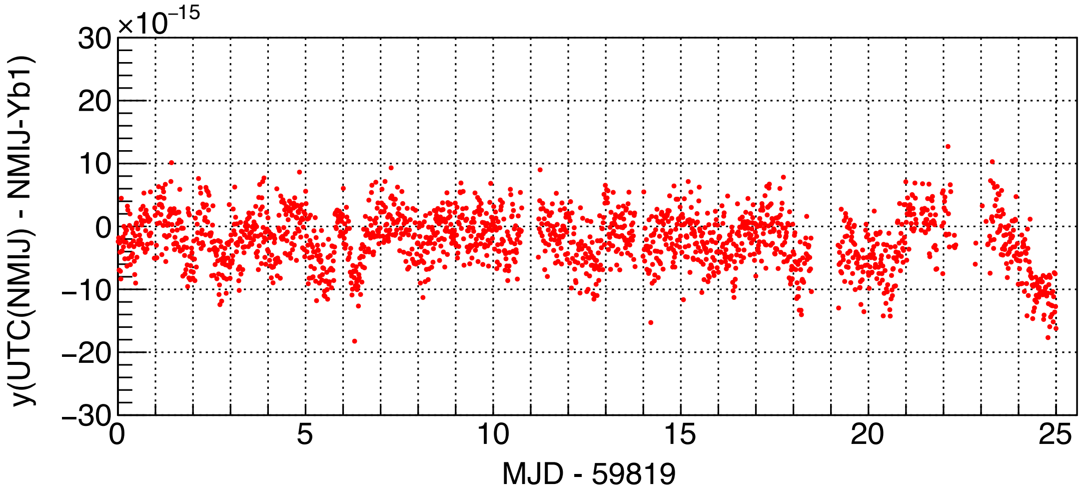

Figure 1. Data points of *y*(UTC(NMIJ) – NMIJ-Yb1) averaged over 10^3 s.

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	5.8	5.3
Blackbody radiation	-251.6	9.7
Density	-1.2	0.6
Second order Zeeman	-5.1	0.3
Probe light	0.5	0.3
Servo error	-3.1	1.1
AOM switching	-	1
Line pulling	-	1
Total	-254.6	11.2
Gravitational redshift	230.8	0.6
Total (with gravitational redshift)	-23.9	11.2

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 ($\sim 3 \times 10^{-16} \rightarrow \sim 6 \times 10^{-17}$). Here we reduced the uncertainty of the magic frequency by a factor of ~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 and after that, 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 ~1×10^{-16} by (a) reducing 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 $\mathrm{m^2/s^2}$. For the reports submitted in July 2022 and after that, the uncertainty of the gravitational redshift was improved from 6×10^{-17} to 6×10^{-18} using the geopotential value of NMIJ-Yb1 measured by Geospatial Information Authority of Japan [4].

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	-	21.6
Steering	0.0	0.0
Total	0.0	21.6

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 $u_{\mathrm{B/Lab}}$ 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 $u_{\mathrm{B/Lab}}$ uncertainty was limited by phase variations of the 10 MHz signal that occurred during its transmission through a coaxial cable.

The uncertainty $u_{\mathrm{A/Lab}}$ arose from the dead time in the comparison between NMIJ-Yb1 and UTC(NMIJ). This uncertainty was estimated using a method described in Ref. [5]. 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 $1 \times 10^{-12} / (\tau/\mathrm{s})$, a white frequency modulation (FM) of $9 \times 10^{-14} / (\tau/\mathrm{s})^{1/2}$, a flicker FM of 2×10^{-15}, a random walk FM of $4 \times 10^{-24} (\tau/\mathrm{s})^{1/2}$. $u_{\mathrm{A/Lab}}$ also includes the uncertainty of a frequency correction resulting from the dead time when the frequency steering of UTC(NMIJ) is carried out.

References

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