

Frequency evaluation of UTC(NMIJ) by NMIJ-Yb1 for the period MJD 59899 to MJD 59909

The secondary frequency standard NMIJ-Yb1 has been compared to UTC(NMIJ), during a measurement campaign between MJD 59899 and MJD 59909 (16th November 2022 – 26th November 2022). The Yb optical lattice clock operation covers 96.2 % of the total measurement period.

1. Results

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

Period (MJD)	$\nu(\text{UTC(NMIJ)} - \text{NMIJ-Yb1})$	Total u_A	Total u_B	$u_{A/\text{Lab}}$	$u_{B/\text{Lab}}$	u_{SecRep}	Uptime (%)
59899 - 59909	-25.1	0.11	1.10	0.6	1.0	1.9	96.2

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

u_A: Type A uncertainty	
Yb statistics	0.11
Total	0.11
u_B: Type B uncertainty	
Yb systematics	1.09
Gravitational	0.06
Total	1.10
$u_{A/\text{Lab}}$: Type A uncertainty	
Dead time in UTC(NMIJ) – Yb	0.6
Total	0.6
$u_{B/\text{Lab}}$: 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]

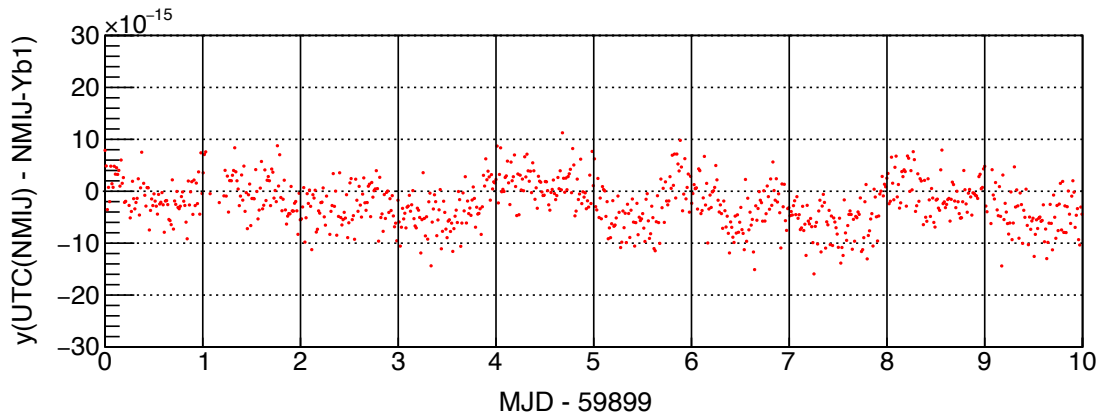


Figure 1. Data points of $y(\text{UTC}(\text{NMIJ}) - \text{NMIJ-Yb1})$ averaged over 10^3 s.

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	5.1	5.7
Blackbody radiation	-250.3	9.1
Density	-1.5	0.8
Second order Zeeman	-5.2	0.3
Probe light	0.5	0.3
Servo error	-3.1	1.4
AOM switching	-	1
Line pulling	-	1
Total	-254.5	10.9
Gravitational redshift	230.8	0.6
Total (with gravitational redshift)	-23.7	11.0

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 $\sim 200E_r$, 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 $\sim 2 \times 10^{-16}$ to $\sim 1 \times 10^{-16}$ 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 °C, 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 $W_0 = 62\,636\,856.0 \text{ m}^2/\text{s}^2$. 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 $\gamma(\text{UTC}(\text{NMIJ}) - \text{NMIJ-Yb1})$ due to the dead time in $\text{UTC}(\text{NMIJ}) - \text{Yb}$ in 1×10^{-17}

Effect	Correction	Uncertainty
Maser noise model	-	6.4
Steering	0.0	0.0
Total	0.0	6.4

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 $\gamma(\text{UTC}(\text{NMIJ}) - \text{NMIJ-Yb1})$.

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

The uncertainty $u_{\text{A/Lab}}$ 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 $1 \times 10^{-12} / (\tau / \text{s})$, a white frequency

modulation (FM) of $9 \times 10^{-14} / (\tau / \text{s})^{1/2}$, a flicker FM of 2×10^{-15} , a random walk FM of $4 \times 10^{-24} (\tau / \text{s})^{1/2}$. $u_{\text{A/Lab}}$ 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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