

## Frequency evaluation of UTC(NMIJ) by NMIJ-Yb1 for the period MJD 59454 to MJD 59464

The secondary frequency standard NMIJ-Yb1 has been compared to UTC(NMIJ), during a measurement campaign between MJD 59454 and MJD 59464 (28<sup>th</sup> August 2021 – 7<sup>th</sup> September 2021). The Yb optical lattice clock operation covers 94.3 % of the total measurement period.

### 1. Results

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

Period (MJD)	$\nu(\text{UTC(NMIJ)} - \text{NMIJ-Yb1})$	Total $u_A$	Total $u_B$	$u_{A/\text{Lab}}$	$u_{B/\text{Lab}}$	$u_{\text{SecRep}}$	Uptime (%)
59454 - 59464	-93.9	0.11	1.20	1.5	1.0	5	94.3

(b) Budget of uncertainties in  $1 \times 10^{-16}$

<b><math>u_A</math>: Type A uncertainty</b>	
Yb statistics	0.11
<b>Total</b>	0.11
<b><math>u_B</math>: Type B uncertainty</b>	
Yb systematics	1.03
Gravitational	0.6
<b>Total</b>	1.20
<b><math>u_{A/\text{Lab}}</math>: Type A uncertainty</b>	
Dead time in UTC(NMIJ) – Yb	1.5
<b>Total</b>	1.5
<b><math>u_{B/\text{Lab}}</math>: Type B uncertainty</b>	
Microwave-optical frequency link	1.0
<b>Total</b>	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  $^{171}\text{Yb}$  neutral atom: 518 295 836 590 863.6 Hz [1].  $u_{\text{SecRep}}$  is the recommended uncertainty of the secondary representation [1]

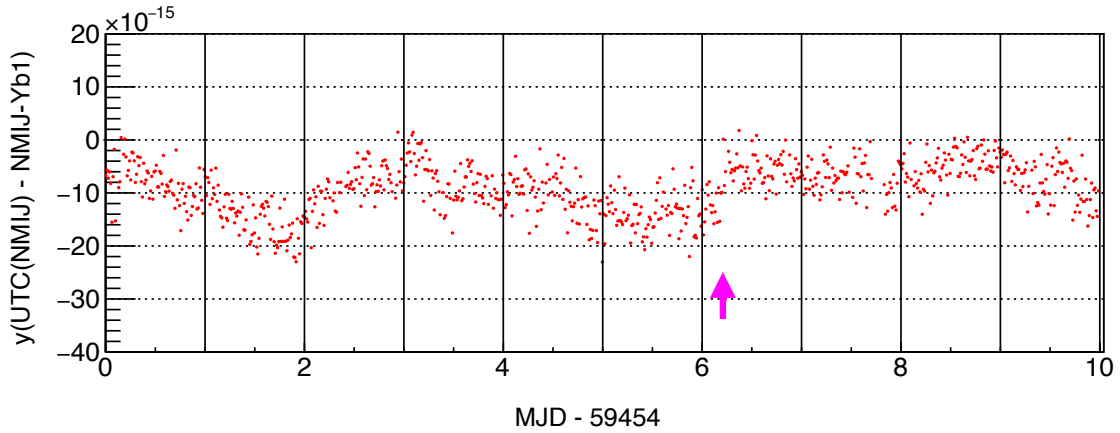


Figure 1. Data points of  $y(\text{UTC}(\text{NMIJ}) - \text{NMIJ-Yb1})$  averaged over  $10^3$  s. The vertical arrow indicates the timing and polarity of the frequency steering of UTC(NMIJ), which is typically carried out by  $5 \times 10^{-15}$ .

## 2. Systematic effects and uncertainties

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

Effect	Shift	Uncertainty
Lattice light	3.6	5.6
Blackbody radiation	-250.2	8.4
Density	-2.2	1.1
Second order Zeeman	-5.1	0.3
Probe light	0.4	0.2
Servo error	-1.5	1.3
AOM switching	-	1
Line pulling	-	1
<b>Total</b>	<b>-255.0</b>	<b>10.3</b>
Gravitational redshift	229.4	6
<b>Total (with gravitational redshift)</b>	<b>-25.6</b>	<b>12.0</b>

For the reports submitted in November and December 2020, the total systematic uncertainty of NMIJ-Yb1 was improved to  $2 \times 10^{-16}$  compared with an uncertainty of  $4 \times 10^{-16}$  described in previous reports and Ref. [3]. A major improvement was made in the uncertainty of the lattice light shift ( $\sim 3 \times 10^{-16} \rightarrow \sim 5 \times 10^{-17}$ ). Here we reduced the uncertainty of the magic frequency by a factor of  $\sim 1/3$ , 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  $1 \times 10^{-16}$ . The uncertainty of the blackbody radiation shift was reduced from  $\sim 2 \times 10^{-16}$  to  $\sim 8 \times 10^{-17}$  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  $\sim 200$  °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  $W_0 = 62\,636\,856.0 \text{ m}^2/\text{s}^2$ .

### 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  $1 \times 10^{-17}$

Effect	Correction	Uncertainty
Maser noise model	-	14.9
Steering	2.5	0.1
<b>Total</b>	2.5	14.9

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  $^{171}\text{Yb}$  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  $1.0 \times 10^{-16}$  compared with an uncertainty of  $2.2 \times 10^{-16}$  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. [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  $1 \times 10^{-12} / (\tau / \text{s})$ , a white frequency

modulation (FM) of  $9 \times 10^{-14} / (\tau / \text{s})^{1/2}$ , a flicker FM of  $2 \times 10^{-15}$ , 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

- [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/utis/common/pdf/mep/171Yb\\_518THz\\_2018.pdf](https://www.bipm.org/utis/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  $^{171}\text{Yb}$  Optical Lattice Clock at NMIJ,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control* **65**, 2449-2458 (2018).
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- [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).