

## Frequency evaluation of UTC(NMIJ) by NMIJ-Yb1 for the period MJD 58939 to MJD 58969

The secondary frequency standard NMIJ-Yb1 has been compared to UTC(NMIJ), during a measurement campaign between MJD 58939 and MJD 58969 (31<sup>st</sup> March 2020 – 30<sup>th</sup> April 2020). The Yb optical lattice clock operation covers 87.2 % 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 (%)
58939 - 58969	5.5	0.07	3.96	1.2	2.2	5	87.2

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

<b><math>u_A</math>: Type A uncertainty</b>	
Yb statistics	0.07
<b>Total</b>	0.07
<b><math>u_B</math>: Type B uncertainty</b>	
Yb systematics	3.92
Gravitational	0.6
<b>Total</b>	3.96
<b><math>u_{A/\text{Lab}}</math>: Type A uncertainty</b>	
Dead time in UTC(NMIJ) – Yb	1.2
<b>Total</b>	1.2
<b><math>u_{B/\text{Lab}}</math>: Type B uncertainty</b>	
Microwave frequency synthesis	2.2
<b>Total</b>	2.2

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]

## 2. Systematic effects and uncertainties

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

Effect	Shift	Uncertainty
Lattice light	3.4	33.1
Blackbody radiation	-263.8	20.8
Density	-2.8	1.9
Second order Zeeman	-5.2	0.3
Probe light	0.4	0.2
Servo error	-2.6	0.9
AOM switching	-	1
Line pulling	-	1
<b>Total</b>	-270.5	39.2
Gravitational redshift	229.4	6
<b>Total (with gravitational redshift)</b>	-41.1	39.6

## 3. Frequency comparison

The frequency comparison between NMIJ-Yb1 and UTC(NMIJ) was carried out using an optical frequency comb. The comb was phase locked to UTC(NMIJ). 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  $\nu(\text{UTC(NMIJ)} - \text{NMIJ-Yb1})$ .

A Type B  $u_{B/\text{Lab}}$  uncertainty arose from microwave frequency synthesis of UTC(NMIJ) which includes frequency multiplication. This uncertainty was estimated by comparisons between two combs with independent setups for the microwave frequency synthesis.

A Type A  $u_{A/\text{Lab}}$  uncertainty arose from the dead time in the comparison between NMIJ-Yb1 and UTC(NMIJ). This uncertainty was estimated using a method described in Ref. [3]. 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  $7 \times 10^{-14} / (\tau / \text{s})^{1/2}$ , a flicker FM of  $2 \times 10^{-15}$ , a random walk FM of  $4 \times 10^{-24} (\tau / \text{s})^{1/2}$ .  $u_{A/\text{Lab}}$  also includes the uncertainty of a frequency correction resulting from the dead time when the frequency steering of UTC(NMIJ) is carried out.

The gravitational redshift was calculated with respect to the conventionally adopted reference

potential  $W_0 = 62\,636\,856.0 \text{ m}^2/\text{s}^2$ .

#### 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).

[3] 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).