# Frequency evaluation of UTC(NMIJ) by NMIJ-Yb1 for the period MJD 58844 to MJD 58879

The secondary frequency standard NMIJ-Yb1 has been compared to UTC(NMIJ), during a measurement campaign between MJD 58844 and MJD 58879 (27th December 2019 – 31st January 2020). The Yb optical lattice clock operation covers 72.7 % of the total measurement period.

## 1. Results

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

| **Period (MJD)** | **$y$(UTC(NMIJ) – NMIJ-Yb1)** | **Total $u_A$** | **Total $u_B$** | **$u_{A/Lab}$** | **$u_{B/Lab}$** | **$u_{SecRep}$** | **Uptime (%)** |
|---|---|---|---|---|---|---|---|
| 58844 - 58879 | 13.5 | 0.07 | 3.97 | 3.3 | 2.2 | 5 | 72.7 |

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

| | |
|---|---|
| **$u_A$ : Type A uncertainty** | |
| Yb statistics | 0.07 |
| **Total** | 0.07 |
| **$u_B$ : Type B uncertainty** | |
| Yb systematics | 3.93 |
| Gravitational | 0.6 |
| **Total** | 3.97 |
| **$u_{A/Lab}$ : Type A uncertainty** | |
| Dead time in UTC(NMIJ) – Yb | 3.3 |
| **Total** | 3.3 |
| **$u_{B/Lab}$ : Type B uncertainty** | |
| Microwave frequency synthesis | 2.2 |
| **Total** | 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 $^{171}$Yb neutral atom: 518 295 836 590 863.6 Hz [1]. $u_{SecRep}$ 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 | -3.9 | 3.0 |
| Second order Zeeman | -5.2 | 0.3 |
| Probe light | 0.4 | 0.2 |
| Servo error | -2.8 | 1.2 |
| AOM switching | - | 1 |
| Line pulling | - | 1 |
| **Total** | -271.9 | 39.3 |
| Gravitational redshift | 229.4 | 6 |
| **Total (with gravitational redshift)** | -42.5 | 39.7 |

## 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 $^{171}$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).

A Type B $u_{B/Lab}$ 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 $u_{A/Lab}$ 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 $1 \times 10^{-12} / (\tau /\mathrm{s})$, a white frequency modulation (FM) of $7 \times 10^{-14} / (\tau /\mathrm{s})^{1/2}$, a flicker FM of $2 \times 10^{-15}$, a random walk FM of $4 \times 10^{-24}$ $(\tau /\mathrm{s})^{1/2}$. $u_{A/Lab}$ also includes the uncertainty of a frequency correction resulting from the dead time when the frequency steering of UTC(NMIJ) is carried out.

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

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/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] 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).