Frequency evaluation of HM1405012 by NMIJ-Yb1
for the period MJD 60039 to MJD 60064

The secondary frequency standard NMIJ-Yb1 has been compared to the hydrogen maser (HM) (clock code: 1405012), during a measurement campaign between MJD 60039 and MJD 60064 (5th April 2023 – 30th April 2023). The Yb optical lattice clock operation covers 87.1 % of the total measurement period.

1. Results

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

Period (MJD)	**y(HM – NMIJ-Yb1)**	**Total u_{A}**	**Total u_{B}**	**$u_{\mathrm{A/Lab}}$**	**$u_{\mathrm{B/Lab}}$**	**u_{SecRep}**	**Uptime (%)**
60039 - 60064	-4278.3	0.07	1.10	0.4	1.0	1.9	87.1

(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	1.09
Gravitational	0.06
Total	1.10
$u_{\mathrm{A/Lab}}$: Type A uncertainty	
Dead time in HM – Yb	0.4
Total	0.4
$u_{\mathrm{B/Lab}}$: 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]

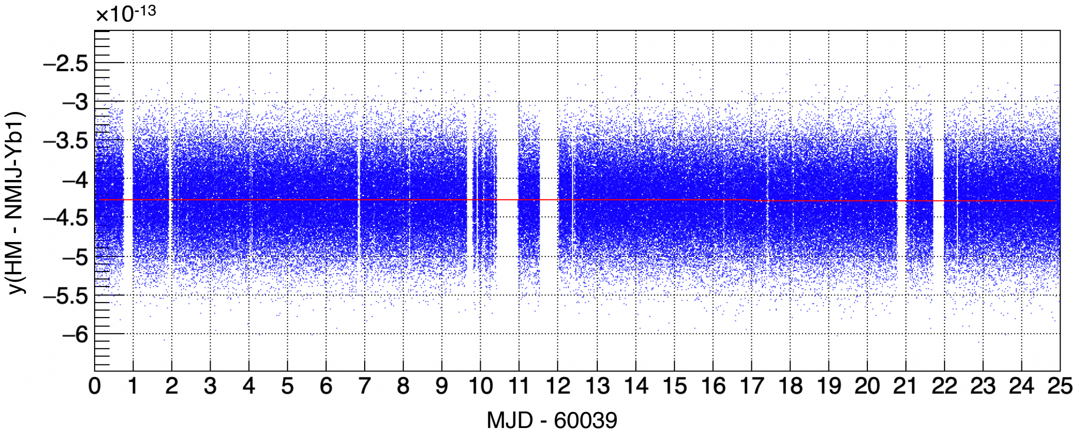

Figure 1. Data points of y(HM – NMIJ-Yb1) averaged over 6.8 s. The red line indicates the linear fit used to obtain the drift rate of HM (typically -1×10^{-16} /d).

2. Systematic effects and uncertainties

Table 2. Budget of systematic effects and uncertainties for NMIJ-Yb1 [2-6] in 1×10^{-17}

Effect	**Shift**	**Uncertainty**
Lattice light	10.3	5.3
Blackbody radiation	-254.2	9.3
Density	-1.1	0.6
Second order Zeeman	-5.2	0.3
Probe light	0.4	1.0
Servo error	-4.8	1.1
AOM switching	-	1
Line pulling	-	1
DC Stark	-	0.1
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 ~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.

For the reports submitted in April 2023, the evaluation of the DC Stark shift was included. The uncertainty of the blackbody radiation shift was slightly improved by using measured surface roughness of the vacuum chamber in the Monte Carlo ray-tracing analysis. The uncertainty of the probe light shift was increased from ~3×10^{-18} to ~1×10^{-17}, taking account of the effect of small residual ellipticity of the probe light which has recently been investigated [4]. A paper describing the improved uncertainty evaluation of NMIJ-Yb1 after November 2020 has been published [5].

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 [6].

3. Frequency comparison

Table 3. Frequency correction and uncertainty for y(HM – NMIJ-Yb1) due to the dead time in HM – Yb in 1×10^{-17}

Effect	**Correction**	**Uncertainty**
Maser noise model	-	3.5
Linear drift	1.0	0.1
Total	1.0	3.5

For the report submitted in April 2023, the frequency of NMIJ-Yb1 was compared with HM instead of 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(HM – 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 HM. This uncertainty was estimated using a method described in Ref. [7]. For this estimation, we derived a maser noise model from the measured stability of HM against NMIJ-Yb1. The model includes a white phase modulation of $3 \times 10^{-13} / (\tau/\mathrm{s})$, a white frequency modulation (FM) of $6 \times 10^{-14} / (\tau/\mathrm{s})^{1/2}$, a flicker FM of 5×10^{-16}, a random walk FM of $2 \times 10^{-27} (\tau/\mathrm{s})^{1/2}$. The $u_{\mathrm{A/Lab}}$ also includes the uncertainty of a frequency correction resulting from the dead time based on the linear drift of HM. The drift rate of HM was determined by fitting the measured data of y(HM – NMIJ-Yb1) with a linear function (see Fig. 1).

References

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