Frequency evaluation of HM1404857 by NIM-Sr1 for the period MJD 60034 to MJD 60064

The frequency of the hydrogen maser HM57, identified by the clock code 1404857, was evaluated during the period MJD 60034 – 60064 (Mar. 31, 2023 – Apr. 30, 2023) that $y_{\mathrm{HM57-Sr1}} = 6.3416 \times 10^{-14}$, using the strontium optical lattice frequency standard NIM-Sr1 and an optical frequency comb.

The evaluation result is made using the CCTF 2021 recommended frequency value 429 228 004 229 872.99 Hz with a relative standard uncertainty of 1.9×10^{-16} [1]. The result is shown in table 1.

Table 1 Result of the evaluation of HM57 by NIM-Sr1

Period of the estimation	$y_{\mathrm{HM57-Sr1}}$ (10^{-16})	u_{A} (10^{-16})	u_{B} (10^{-16})	$u_{\mathrm{A/lab}}$ (10^{-16})	$u_{\mathrm{B/lab}}$ (10^{-16})	u_{Srep} (10^{-16})	uptime (%)
MJD 60034 – 60064	634.16	<0.1	0.33	2.3	0.6	1.9	21.0

1 NIM-Sr1 evaluation

NIM-Sr1 is operated as described in ref [2] with some changes described below.

The type A uncertainty u_{A} is the statistical contribution from the frequency instability of NIM-Sr1. It is estimated based on a dominating white frequency noise component of $1.8 \times 10^{-15}/\sqrt{\tau}$ [2], and less than 1.0×10^{-17} after extrapolated to the duration of the evaluation period.

The type B uncertainty u_{B} is the sum of the systemic uncertainty of NIM-Sr1 for the evaluation period. The systemic uncertainty of the NIM-Sr1 is given in table 2.

Table 2 Budget of systematic effects and uncertainties for the MJD 60034-60064

Systematic effect	Correction (10^{-17})	Uncertainty (10^{-17})
BBR MOT chamber	491.8	1.6
BBR oven and heated ZS window	1.0	0.4
Lattice light	1.8	1.2

Collisions	8.1	1.4
2nd Zeeman	20.1	0.3
Background gas collisions	2.1	0.3
DC Stark	2.1	<0.1
Probe AC Stark	0	<0.1
Servo error	0	<0.1
Tunnelling	0	<0.1
Total	**527.0**	**2.5**
Relativistic redshift	-509.4	2.2
Total (with relativistic redshift)	**17.6**	**3.3**

The BBR shift

The temperature of the oven is set to 723.15 K (50 K lower than ref [2]) because the atoms loaded in the lattice are enough for the measurement. The temperature of chamber is measured to be 294.31 K, about 2 K lower than ref 2, which results in a decrease of the BBR shift. The correction of BBR is $491.8(1.6) \times 10^{-17}$ in the evaluation period.

The lattice light shift

The frequency of the lattice is stabilized to the frequency comb with a frequency detuning of about 10(2) MHz above the magic wavelength. The lattice light shift was re-evaluated based on the ref [3]. The correction is re-evaluated to be $1.8(1.2) \times 10^{-17}$.

The collisional shift

The atom number in the lattice is a little different from the previous evaluation. The collisional shift and its uncertainty were estimated with the same method in ref 2. The correction is $8.1(1.4) \times 10^{-17}$ in the evaluation period.

The 2nd Zeeman shift

In the evaluation period, the frequency difference between the $m_F = 9/2$ and $m_F = -9/2$ components is 589 Hz, a little lower than ref 2. The 2nd Zeeman shift correction is estimated to be $20.1(0.3) \times 10^{-17}$.

The relativistic redshift

The relativistic redshift is computed with respect to W_0 = 62636856.0 m^2s^{-2} of the Earth's gravity potential defining the rate of TT/TAI. The relativistic potential at the mean sea level at the tide gauge station in Qingdao, China is W_{QB} = 62636852.95 (0.49) m^2s^{-2}[4]. The averaged local gravity acceleration is 9.80125(1) ms^{-2}. The average height of the atoms is 46.4(0.2) m which is measured by the dimensional metrology laboratory of NIM and traced to a leveling benchmark inside our campus [2]. The relativistic redshift correction is computed by $(W_{QB} - gh - W_0)/c^2$, which is $-509.4(2.2) \times 10^{-17}$.

2 Frequency comparison

The measurement was carried out with an optical frequency comb that was phase-locked to NIM-Sr1, and the multiples of the comb's repetition frequency were subsequently measured with reference to HM57. The reference signal was transferred by a fiber link from maser lab at Changping to the optical clock lab at Hepingli. The 10 MHz reference signal is multiplied to 980 MHz based on the low phase noise Dielectric Resonator Oscillator (DRO) in our comb. The differential frequency $\Delta = 4 \cdot f_{\mathrm{rep}} - 980\ \mathrm{MHz}$ was measured with a K&K commercial phase and frequency meter. The average value and its uncertainty were calculated every weekday. A final weighted average value was calculated over the evaluation period.

The most significant source of uncertainty $u_{\mathrm{A/lab}}$ arises from the dead time due to the intermittent operation of the optical clock and the comb, includes both a deterministic correction due to maser drift and a stochastic contribution. The uncertainty due to the dead-time in the comparison was estimated following the procedure in [5]. The noise model of HM57 estimated comprises a white phase noise of $1.0 \times 10^{-13}\ (\tau/s)^{-1}$, a white frequency noise of $4.5 \times 10^{-14}\ (\tau/s)^{-1/2}$, a flicker frequency noise of 3.0×10^{-16} and a random-walk frequency noise of $3.8 \times 10^{-19}\ (\tau/s)^{1/2}$ [6].

Table 3 A breakdown of the uncertainties included in $u_{\mathrm{A/lab}}$

$u_{\mathrm{A/lab}}$ (10^{-16})	
Extrapolation (dead time)	1.09
Extrapolation (drift)	0.12
Sr1-HM comparison	2.06
Total	2.3

The most significant contribution to the uncertainty $u_{\mathrm{B/lab}}$ is the synthesis and distribution of the microwave frequency reference. The uncertainty introduced by the optical frequency synthesis of the comb has been assessed to be well below 10^{-18} [7], but the microwave setup of the comb may lead to inaccuracy. The 10 MHz reference signal is multiplied to 980 MHz based on a low phase noise DRO in our comb. The frequency synthesis uncertainty is assessed by comparing the 980 MHz signal from DRO with a 989 MHz signal generated by a frequency synthesizer (SMA100B) that shares the same reference with the DRO. The two signals were mixed down to 9 MHz, and compared with the 10 MHz reference using a Phase Noise Analyzer (Microchip 53100A). The frequency synthesis uncertainty is estimated to be below 5×10^{-17}. Another source of uncertainty arises from the counting error. The counting error is assessed by measuring the 10 MHz maser signal, also used as the counter's external reference. This counting error contributes an uncertainty of less than 3×10^{-16} for Δ (about 20 MHz), leading to an uncertainty of $< 3 \times 10^{-17}$ for 250 MHz (corresponding to the $f$rep frequency). The combined uncertainty induced by the frequency comb and counter of the $f$rep is less than 6×10^{-17}. The uncertainty induced by the fiber link for microwave transmission is measured to be less than $<1\times10^{-17}$ by comparing two microwave signals that are both transferred from maser lab to the optical clock lab through two fiber cores in the same fiber link.

Table 4 A breakdown of the uncertainties included in $u_{\mathrm{B/lab}}$

$u_{\mathrm{B/lab}}$ (10^{-16})	
Frequency comb + counting	<0.6

Microwave transmission	< 0.1
Total	0.6

Reference:

[1] Consultative Committee for Time and Frequency (CCTF), "Recommendation PSFS-2 from the 22nd meeting (session II – online)," (2022).
[2] Y. Lin, Q. Wang, et al. "A ^{87}Sr optical lattice clock with 2.9×10^{-17} uncertainty and its absolute frequency measurement", *Metrologia,* **58,** 035010 (2021)
[3] I. Ushijima, et al, "Operational magic intensity for Sr optical lattice clocks", Physical Review Letters, 121, 263208 (2018)
[4] L. He et al, "Evaluation of the geopotential value W_0^{LVD} of China", *Geodesy and Geodynamics,* **8,** 408-412 (2017)
[5] D.-H. Yu et al, "Uncertainty of a frequency comparison with distributed dead time and measurement interval offset", *Metrologia*, **44**, 91 (2007)
[6] L. Zhu, et al. "Preliminary study of generating a local time scale with NIM ^{87}Sr optical lattice clock", *Metrologia,* **59** 055007 (2022)
[7] E. Benkler, et al, "End to end toplogy for fiber comb based optical frequency transfer at 10^{-21} level", *Optics Express,* **27**, pp: 36886-36902 (2019).