Frequency evaluation of UTC(NPL) by NPL-E3Yb+3 for the period MJD 59649 to 59669

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The secondary frequency standard NPL-E3Yb+3 and an optical frequency comb were used to evaluate the frequency of UTC(NPL) over a period of 20 days from MJD 59649 to MJD 59669 (11th March 2022 − 31st March 2022). The Yb^+ ion optical clock operation covers 42.58 % of the total measurement period. The result of the evaluation is reported in table 1 and is made using the CCTF 2021 recommended frequency value for the $4f^{14}6s\ ^2S_{1/2}$ − $4f^{13}6s^2\ ^2F_{7/2}$ (E3) unperturbed optical transition in $^{171}Yb^+$: 642 121 496 772 645.12 Hz with a relative standard uncertainty of $u_{\mathrm{Srep}} = 1.9 \times 10^{-16}$ [1].

Table 1: Results of the evaluation of UTC(NPL) by NPL-E3Yb+3

Period of estimation	y(UTC(NPL)− NPL-E3Yb+3 /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 59649–59669	−4.64	0.075	0.040	6.56	0.52	1.9	42.58 %

1 Measurement configuration

The operation of NPL-E3Yb+3 is described in sections 2 and 4.5 of [2]. The electric octupole (E3) transition of $^{171}Yb^+$ was probed with a clock laser at 467 nm, frequency-doubled from 934 nm. The 934 nm laser was prestabilised to a local cavity and then further stabilised to a 1064 nm ultrastable laser [3] via an optical frequency comb. A feedback loop acting on an acousto-optic modulator (AOM) kept the clock laser frequency in resonance with the $^{171}Yb^+$ clock transition.

The optical frequency comb was used to measure the 934 nm laser frequency relative to the reference frequency of the comb. In January 2021, the reference maser for UTC(NPL) was changed from HM2 to HM4, and shortly afterwards the reference for the frequency comb was changed to the unsteered output of another maser, HM6. The frequency ratio between NPL-E3Yb+3 and HM6 was therefore evaluated using the comb measurements of the 934 nm light and the AOM frequency corrections, while the offset between HM6 and UTC(NPL) was measured with a phase comparator.

2 NPL-E3Yb+3 evaluation

Type A uncertainty

The type A uncertainty u_A is the statistical contribution from the frequency instability of NPL-E3Yb+3. This was estimated based on a white frequency noise component of $6.4\times10^{-15}/\sqrt{\tau}$ extrapolated to the duration of the evaluation period. This stability was measured based on the Allan deviation of the frequency ratio with the local optical lattice clock NPL-Sr1. The reason why this frequency instability is particularly high compared to the previous report (MJD 58664−58674) is because the probe duration was incorrectly set to be too long for both the high- and low- power servos, so did not produce π-pulses.

Type B uncertainty

The type B uncertainty u_B is the sum in quadrature of the systematic uncertainty of NPL-E3Yb+3 and the uncertainty of the relativistic redshift relative to the conventionally adopted reference potential $W_0 = 62\ 636\ 856.0\ \mathrm{m^2s^{-2}}$.

The full systematic uncertainty evaluation of NPL-E3Yb+3 is described in section 3 of [2], and any differences in the systematic shift measurements for the period MJD 59649–59669 are outlined in section 4.5. The systematic frequency corrections and uncertainty budget for NPL-E3Yb+3 for the period of this report are given in table 2. The geopotential value for NPL-E3Yb+3 is evaluated based on the ion being 1.029(1) m above a reference marker in the floor of laboratory G4-L16. The geopotential of the reference marker is taken from [4].

3 Frequency comparison

Type A uncertainty

The uncertainty $u_{\mathrm{A/Lab}}$ arises mainly from the dead time in the comparison between HM6 and NPL-E3Yb+3, and includes both a deterministic correction due to maser drift and a stochastic contribution (table 3).

The analysis method for the deterministic downtime correction is described in detail in section 5.2.2 of [5]. The maser HM6 was drifting linearly throughout the measurement period. The correction was calculated as the difference between the mean of the linear fit to the maser frequency during the uptime of NPL-E3Yb+3 and the mean of the linear fit during the entire measurement period MJD 59649–59669.

For this evaluation period, NPL-E3Yb+3 had an uptime of 42.58 %, distributed as shown in figure 1.

In contrast to the earlier report covering the period MJD 58664 – 58674, the stochastic contribution was estimated by a method described in reference [6]. This involves a Monte-Carlo approach where the frequency noise of HM6 is simulated 100 times, with

Table 2: Uncertainty budget for the Yb^+ ion optical clock for this evaluation period. The corrections show the frequency adjustments made post-analysis, which are in addition to dynamic corrections that are made on the fly. Reported uncertainties correspond to 68% confidence intervals. This table applies to the period MJD 59649–59669.

Systematic effect	**Correction** / 10^{-18}	**Uncertainty** / 10^{-18}
Electric quadrupole	-22.3	2.8
Black-body radiation	0	1.2
Background gas collisions	0	0.6
Quadratic Zeeman (DC)	0	0.6
Second-order Doppler	1.5	0.4
AC Stark - probe beam	0	0.3
Phase chirp	0	0.2
Quadratic Zeeman (AC)	0.3	0.2
Trapping RF Stark	0.34	0.07
AC Stark - overshoot	-0.07	0.07
Servo offset	0	0.06
Trap-induced AC Zeeman	< 0.01	< 0.01
AC Stark - leakage light	< 0.01	< 0.01
Total correction	**-20.3**	**3.2**
Relativistic redshift	-1186.9	2.5
Total including relativistic redshift	**-1207.2**	**4.0**

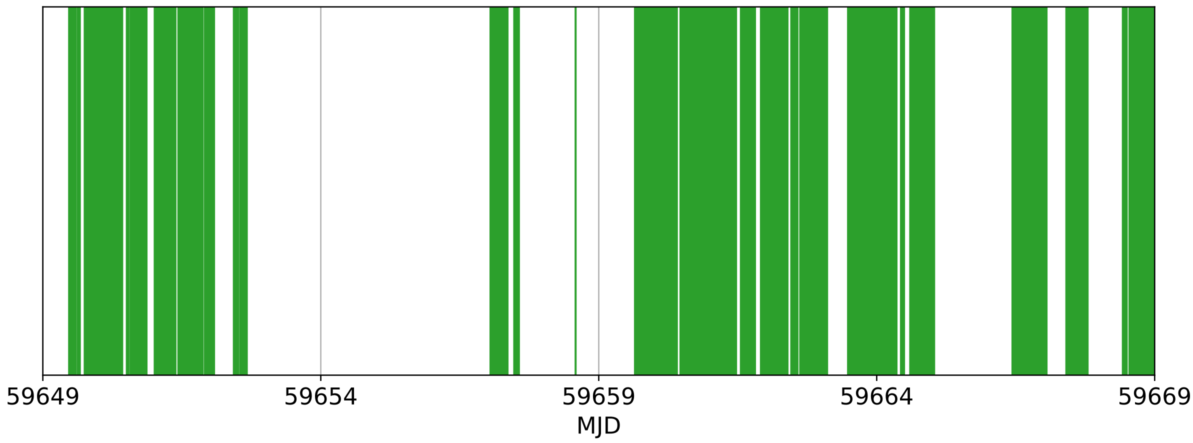

Figure 1: Uptime of NPL-E3Yb+3 over the evaluation period (green regions).

the standard deviation of the offsets providing an estimate for the frequency uncertainty arising from the dead times in the operation of NPL-E3Yb+3.

The maser noise model used comprised white phase noise of $1.25\times10^{-13}/\tau$, white frequency noise of $4.90\times10^{-14}/\sqrt{\tau}$, and a flicker frequency floor of 1.50×10^{-15}. In addition, maser HM6 exhibited periodic frequency fluctuations that were estimated as an additional noise process proportional to the sum of four sinusoids in the simulated noise, with amplitudes 1.0×10^{-15}, $1.9\times\ 10^{-15}$, 2.1×10^{-15}, 2.7×10^{-15} and periods 3×10^{3} s, 3×10^{4} s, 8.64×10^{4} s, and 1.728×10^{5} s respectively.

This method for modelling maser noise is better suited to handling periodic frequency fluctuations, compared with the method used in [2] that simply raised the flicker floor and did not include sinusoidal contributions. The method in [2] resulted in an overly conservative approach to dealing with bumps in the Allan deviation and hence the stochastic contribution to $u_{\mathrm{A/Lab}}$ reported here is lower.

The TimeTech phase comparator that measures the offset between HM6 and UTC(NPL) introduces an additional contribution to $u_{\mathrm{A/Lab}}$, which is computed from the instability of the phase difference of UTC(NPL) referenced to itself.

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{A/Lab}}$[Deterministic]	102
$u_{\mathrm{A/Lab}}$[Stochastic]	648
$u_{\mathrm{A/Lab}}$[HM6-UTC(NPL)]	13
$u_{\mathrm{A/Lab}}$[Total]	656

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

Type B uncertainty

The most significant contribution to the uncertainty $u_{\mathrm{B/Lab}}$ is the distribution of the 10 MHz signal from HM6 to the frequency comb laboratory, and the subsequent synthesis in that laboratory of an 8 GHz signal against which the repetition rate of the frequency comb was measured. Potential phase fluctuations were monitored using a loop-back comparison as described in reference [7], and their contribution to the uncertainty estimated from the instability of these fluctuations over the evaluation period.

The TimeTech phase comparator that measures the offset between HM6 and UTC(NPL) also contributes to $u_{\mathrm{B/Lab}}$. This contribution is estimated based on the specification of the instrument. Note that this differs from the uncertainty reported in [2], which had assumed a larger uncertainty for the instrument.

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{B/Lab}}$[Distribution]	51
$u_{\mathrm{B/Lab}}$[HM6-UTC(NPL)]	7
$\boldsymbol{u_{\mathrm{B/Lab}}}$**[Total]**	52

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

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