Frequency evaluation of UTC(NPL) by NPL-E3Yb+3 for the period MJD 60004 to 60034

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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 30 days from MJD 60004 to MJD 60034 (1st March 2023 − 31st March 2023). The Yb^+ ion optical clock operation covers 65.68 % 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 60004–60034	−0.54	0.023	0.033	2.79	0.58	1.9	65.68 %

1 Measurement configuration

The operation of NPL-E3Yb+3 is described in section 2 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, which was supplied from the unsteered output of maser HM6. However, in contrast to the earlier report covering the period MJD 59649–59669, UTC(NPL) was the steered output of HM6. The frequency ratio between NPL-E3Yb+3 and the unsteered frequency from HM6 was therefore evaluated using the comb measurements of the 934 nm light and the AOM frequency corrections. The offset between the unsteered frequency from HM6 and the steered frequency, 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 $3.05\times10^{-15}/\sqrt{\tau}$ 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.

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 uncertainty evaluation of NPL-E3Yb+3 is described in [2], and 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 these two contributions is described in detail in section 5.2.2 of [5]. The maser HM6 was drifting linearly throughout the measurement period. The deterministic downtime 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 60004–60034.

The maser noise model used comprised white phase noise of $2.0\times10^{-13}/\tau$, white frequency noise of $5.4\times10^{-14}/\sqrt{\tau}$, and a flicker frequency floor of 2.0×10^{-15}. The method used to determine the stochastic downtime uncertainty is similar to that described in [6]. The fast Fourier transform of the data validity array is multiplied by the power spectral

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 60004–60034.

Systematic effect	**Correction** / 10^{-18}	**Uncertainty** / 10^{-18}
Electric quadrupole	−22.8	1.5
Black-body radiation	0	1.2
Quadratic Zeeman (DC)	29.2	0.6
Background gas collisions	0	0.6
Phase chirp	0	0.5
AC Stark - probe beam	0	0.4
Second-order Doppler	0	0.3
Trapping RF Stark	0	0.06
Servo offset	0	0.05
Quadratic Zeeman (AC)	0.14	0.05
Trap-induced AC Zeeman	< 0.01	< 0.01
AC Stark - overshoot	−0.08	< 0.01
AC Stark - leakage light	< 0.01	< 0.01
Total correction	**6.5**	**2.2**
Relativistic redshift	−1186.9	2.5
Total including relativistic redshift	**−1180.4**	**3.3**

density calculated from the maser model such that the root mean square fluctuation can be extrapolated to the full evaluation period.

For this evaluation period, NPL-E3Yb+3 had an uptime of 65.68 %, distributed as shown in figure 1.

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 stability of the phase difference of UTC(NPL) referenced to itself.

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.

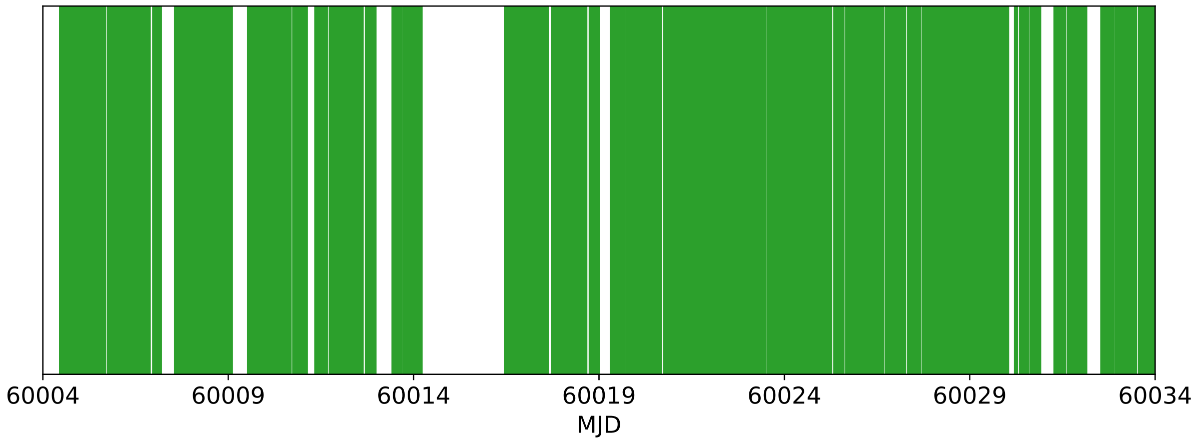

Figure 1: Uptime of NPL-E3Yb+3 over the evaluation period (green regions).

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{A/Lab}}$[Deterministic]	18
$u_{\mathrm{A/Lab}}$[Stochastic]	278
$u_{\mathrm{A/Lab}}$[HM6-UTC(NPL)]	8
$\boldsymbol{u_{\mathrm{A/Lab}}}$**[Total]**	279

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

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]	58
$u_{\mathrm{B/Lab}}$[HM6-UTC(NPL)]	5
$\boldsymbol{u_{\mathrm{B/Lab}}}$**[Total]**	58

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

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