Frequency evaluation of UTC(NPL) by NPL-E3Yb+3 for the period MJD 60599 to 60614

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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 15 days from MJD 60599 to MJD 60614 (16th October 2024 − 31st October 2024). The Yb^+ ion optical clock operation covers 62.93 % 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 $4f^{14}6s\ ^2S_{1/2} - 4f^{13}6s^2\ ^2F_{7/2}$ 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 60599–60614	−3.48	0.017	0.031	3.25	0.73	1.9	62.93 %

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 the unsteered output of the maser HM6. The steered output of HM6 was used to generate UTC(NPL). 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 steered and unsteered signals from HM6 was measured by a phase comparator throughout the measurement period.

Compared to the previous report covering the period MJD 60004–60034, there are two main differences in the clock operation. First of all, the E3 transition was interrogated with longer probes, namely 440 ms and 900 ms respectively in the high-power and low-power servos, and with a power ratio close to 4:1 between them. This increase in probe time, while maintaining a high level of coherence (80-90% peak excitation of the clock transition), was made possible with a reduced trap heating rate, which was achieved by increasing the secular frequencies with a higher RF trap drive amplitude.

The second difference is the use of a new supercontinuum-based optical frequency comb (Universal Synthesiser 2.0), following its installation just before the start of this evaluation period. A comparison of the NPL-Sr1/HM6 ratio data measured by each comb demonstrated a comb agreement of $1.2(1.9) \times 10^{-18}$, showing that this contribution to $u_{\mathrm{B/Lab}}$ is negligible compared to the typical dominating uncertainty.

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 $1.5{\times}10^{-15}/\sqrt{\tau}$ extrapolated to the duration of the evaluation period. The frequency stability is based on the Allan deviation of the frequency ratio with the local optical lattice clock NPL-Sr1, measured in November 2024 with the same probing parameters.

The improvement in frequency stability compared to the previous report covering the period MJD 60004–60034 ($3.05{\times}10^{-15}/\sqrt{\tau}$) mainly comes from the increase in probe duration and excitation fraction of the clock transition.

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].

Changes to the uncertainty evaluation presented in reference [2] are described below.

Electric quadrupole shift

Since October 2024, the measurement of the electric quadrupole shift has been simplified and has become more direct. Previously, the E2 transition was probed in 5 alternating magnetic field directions in order to fit the electric field gradient and calculate the electric quadrupole shift in the y-direction, which is the quantisation axis direction used for probing the E3 transition. Changes in optical setups have enabled the direct probing of the E2 in the y-direction, reducing the required number of magnetic fields from 5 to 3, and allowing the direct measurement of the shift without the need for a fit.

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 60599–60614.

Systematic effect	**Correction** $/10^{-18}$	**Uncertainty** $/10^{-18}$
Black-body radiation	0	1.2
Electric quadrupole	−22.8	0.7
Background gas collisions	0	0.6
Quadratic Zeeman (DC)	28.9	0.6
Second-order Doppler	1.7	0.4
AC Stark - probe beam	0	0.3
Phase chirp	0	0.2
Trap-induced AC Zeeman	0	0.1
Quadratic Zeeman (AC)	0.14	0.10
Trapping RF Stark	0.38	0.09
Servo offset	0	0.06
AC Stark - overshoot	−0.03	0.03
AC Stark - leakage light	< 0.01	< 0.01
Total correction	**8.3**	**1.8**
Relativistic redshift	−1186.9	2.5
Total including relativistic redshift	**−1178.6**	**3.1**

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 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 60599–60614.

In contrast to the earlier report covering the period MJD 60004–60034, 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 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. This approach is more suitable for dealing with the additional noise sources seen in the maser this month, described below.

The maser noise model used comprised white phase noise of $1.20\times10^{-13}/\tau$, white frequency noise of $5.00\times10^{-14}/\sqrt{\tau}$, and a flicker frequency floor of 1.40×10^{-15}. In addition, maser HM6 exhibits periodic frequency fluctuations that were estimated as an additional noise process proportional to the sum of three sinusoids in the simulated noise, with amplitudes 1.8×10^{-15}, 1.9×10^{-15}, 1.5×10^{-15} and periods 3×10^{4} s, 8.64×10^{4} s, and 1.728×10^{5} s respectively. These values were derived from measurements of HM6 by NPL-E3Yb+3 during the evaluation period.

For this evaluation period, NPL-E3Yb+3 had an uptime of 62.93 %, 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.

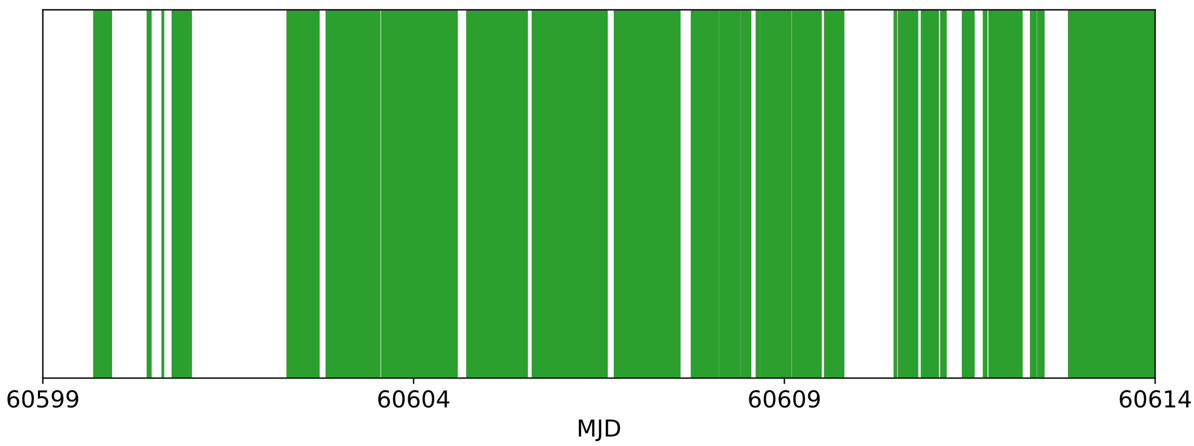

Figure 1: Uptime of NPL-E3Yb+3 over the evaluation period (green regions).

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{A/Lab}}$[Deterministic]	103
$u_{\mathrm{A/Lab}}$[Stochastic]	307
$u_{\mathrm{A/Lab}}$[HM6-UTC(NPL)]	18
$\boldsymbol{u}_{\mathbf{A/Lab}}$**[Total]**	325

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.

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{B/Lab}}$[Distribution]	72
$u_{\mathrm{B/Lab}}$[HM6-UTC(NPL)]	9
$\boldsymbol{u}_{\mathbf{B/Lab}}$**[Total]**	73

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

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