Frequency evaluation of UTC(NPL) by NPL-E3Yb+3 for the period MJD 58664 to 58674

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March 18, 2025

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 10 days from MJD 58664 to MJD 58674 (30th June 2019 − 10th July 2019). The Yb^+ ion optical clock operation covers 40.76 % 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 58664–58674	−7.40	0.040	0.073	6.28	1.00	1.9	40.76 %

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, which was UTC(NPL), generated by the maser HM2. The frequency ratio between NPL-E3Yb+3 and UTC(NPL) was therefore evaluated using the comb measurements of the 934 nm light and the AOM frequency corrections.

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 $2.4\times10^{-15}/\sqrt{\tau}$ 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.

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 58664–58674 are outlined in section 4.5. The systematic frequency corrections and uncertainty budget for NPL-E3Yb+3 for this period 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 HM2 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]. Because frequency steers were applied to UTC(NPL) during the evaluation period of this report, these had to be taken into account when calculating the deterministic downtime correction and its uncertainty. The steers were subtracted from the data such that the linear drift of the maser could be estimated. The frequency steers were then added back into the fitted line, and the downtime correction was calculated as the difference between the mean fitted maser frequency during the uptime of NPL-E3Yb+3 and the mean fitted maser frequency during the entire measurement period MJD 58664–58674.

The maser noise model used comprised white phase noise of $4.0\times10^{-13}/\tau$, white frequency noise of $14.0\times10^{-14}/\sqrt{\tau}$, and a flicker frequency floor of 0.9×10^{-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. Reported uncertainties correspond to 68% confidence intervals. This table applies to the period MJD 58664–58674.

Systematic effect	**Correction** / 10^{-18}	**Uncertainty** / 10^{-18}
Electric quadrupole	-1.7	6.2
Phase chirp	0	2.2
Black-body radiation	66.4	1.2
Servo offset	0	0.9
Background gas collisions	0	0.6
Quadratic Zeeman (DC)	29.4	0.6
AC Stark - probe beam	0	0.4
Second-order Doppler	1.3	0.4
AC Stark - overshoot	0	0.1
Quadratic Zeeman (AC)	0.3	0.1
Trapping RF Stark	0.31	0.09
Trap-induced AC Zeeman	< 0.01	< 0.01
AC Stark - leakage light	< 0.01	< 0.01
Total correction	**96.0**	**6.9**
Relativistic redshift	-1186.9	2.5
Total including relativistic redshift	**-1090.9**	**7.3**

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 40.76 %, distributed as shown in figure 1.

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{A/Lab}}$[Deterministic]	274
$u_{\mathrm{A/Lab}}$[Stochastic]	566
$\boldsymbol{u_{\mathrm{A/Lab}}}$**[Total]**	628

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 HM2 to the frequency comb laboratory, and the subsequent synthesis

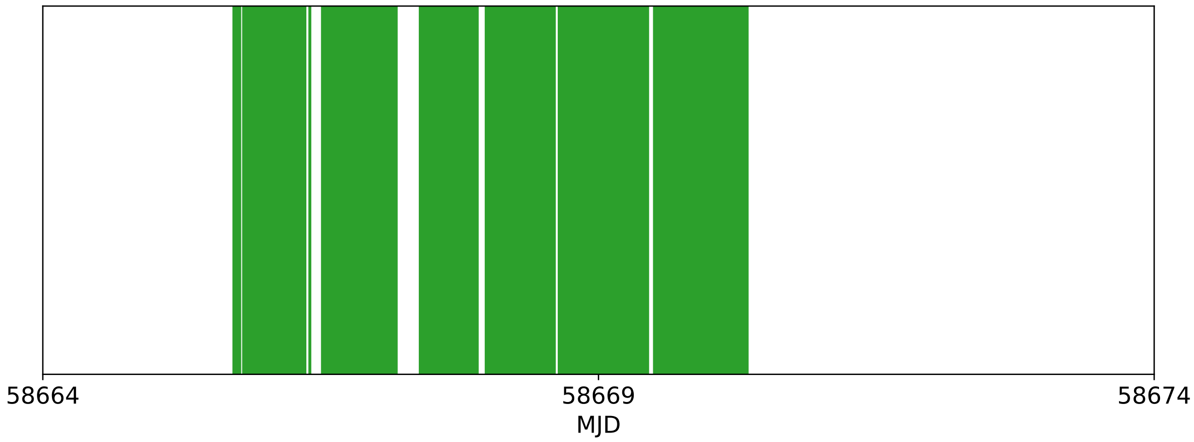

Figure 1: Uptime of NPL-E3Yb+3 over the evaluation period (green regions).

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.

References

[1] H S Margolis, G Panfilo, G Petit, C Oates, T Ido, and S Bize. The CIPM list 'Recommended values of standard frequencies': 2021 update. *Metrologia*, 61(3):035005, 2024.

[2] A Tofful, C F A Baynham, E A Curtis, A O Parsons, B I Robertson, M Schioppo, J Tunesi, H S Margolis, R J Hendricks, J Whale, R C Thompson, and R M Godun. $^{171}Yb^{+}$ optical clock with 2.2×10^{-18} systematic uncertainty and absolute frequency measurements. *Metrologia*, 61(4):045001, 2024.

[3] M. Schioppo, J. Kronjäger, A. Silva, R. Ilieva, J. W. Paterson, C. F.A. Baynham, W. Bowden, I. R. Hill, R. Hobson, A. Vianello, M. Dovale-Álvarez, R. A. Williams, G. Marra, H. S. Margolis, A. Amy-Klein, O. Lopez, E. Cantin, H. Álvarez Martínez, R. Le Targat, P. E. Pottie, N. Quintin, T. Legero, S. Häfner, U. Sterr, R. Schwarz, S. Dörscher, C. Lisdat, S. Koke, A. Kuhl, T. Waterholter, E. Benkler, and G. Grosche. Comparing ultrastable lasers at 7×10^{-17} fractional frequency instability through a 2220 km optical fibre network. *Nature Communications*, 13(1):212, 2022.

[4] F. Riedel, A. Al-Masoudi, E. Benkler, S. Dörscher, V. Gerginov, C. Grebing, S. Häfner, N. Huntemann, B. Lipphardt, C. Lisdat, E. Peik, D. Piester, C. Sanner, C. Tamm, S. Weyers, H. Denker, L. Timmen, C. Voigt, D. Calonico, G. Cerretto, G. A. Costanzo, F. Levi, I. Sesia, J. Achkar, J. Guéna, M. Abgrall, D. Rovera, B. Chupin, C. Shi, S. Bilicki, E. Bookjans, J. Lodewyck, R. Le Targat, P. Delva, S. Bize, F. N. Baynes, C. F. A. Baynham, W. Bowden, P. Gill, R. M. Godun, I. R. Hill, R. Hobson, J. M. Jones, S. A. King, P. B. R. Nisbet-Jones, A. Rolland, S. L. Shemar, P. B. Whibberley, and H. S. Margolis. Direct comparisons of European primary and secondary frequency standards via satellite techniques. *Metrologia*, 57(4):045005, 2020.

[5] A Tofful. *Advances in performance and automation of a single ytterbium ion optical clock*. PhD thesis, Imperial College London, 2023.

[6] C. Grebing, A. Al-Masoudi, S. Dörscher, S. Häfner, V. Gerginov, S. Weyers, B. Lipphardt, F. Riehle, U. Sterr, and C. Lisdat. Realization of a timescale with an accurate optical lattice clock. *Optica*, 3(6):563–569, 2016.

[7] R. Hobson, W. Bowden, A. Vianello, A. Silva, C. F. A. Baynham, H. S. Margolis, P. E. G. Baird, P. Gill, and I. R. Hill. A strontium optical lattice clock with 1×10^{-17} uncertainty and measurement of its absolute frequency. *Metrologia*, 57(6):065026, Dec 2020.