Frequency evaluation of UTC(NPL) by NPL-Sr1 for the period MJD 58454 to MJD 58459

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The secondary frequency standard NPL-Sr1 and an optical frequency comb were used to evaluate the frequency of UTC(NPL) over a period of 5 days from MJD 58454 to MJD 58459 (2^{nd} December 2018 – 7^{th} December 2018). The Sr optical lattice clock operation covers 49.2% 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 $5s^2\ ^1S_0$ – $5s5p\ ^3P_0$ unperturbed optical transition in ^{87}Sr: 429 228 004 229 872.99 Hz with a relative standard uncertainty of $u_{\mathrm{Srep}} = 1.9 \times 10^{-16}$ [1].

Period of estimation	y(UTC(NPL)−NPL-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 58454–58459	−4.41	0.017	0.11	3.66	1.52	1.9	49.2%

Table 1: Results of the evaluation of UTC(NPL) by NPL-Sr1.

1 Measurement configuration

NPL-Sr1 was operated as described in reference [2], with the exception of some changes described in section 2 below. The 698 nm clock laser was pre-stabilized to a local reference cavity and then phase-locked via a fibre-based optical frequency comb to another more stable laser at 1064 nm. A feedback loop acting on an acousto-optic modulator (AOM) kept the clock laser frequency in resonance with the ^{87}Sr clock transition. The optical frequency comb was referenced to UTC(NPL), and the frequency ratio between the ^{87}Sr clock transition and UTC(NPL) was calculated from the comb measurements of the 698 nm ultrastable laser and the AOM frequency corrections. The reported frequency value is determined as the average of a sawtooth fit to the NPL-Sr1/UTC(NPL) ratio data, which includes frequency steps corresponding to the known times and magnitudes of the maser frequency steers.

2 NPL-Sr1 evaluation

Type A uncertainty

The type A uncertainty u_A is the statistical contribution from the frequency instability of NPL-Sr1. This was estimated based on a white frequency noise component of $8 \times 10^{-16}/\sqrt{\tau}$, extrapolated to the duration of the evaluation period.

Systematic effect	Correction / 10^{-18}	Uncertainty / 10^{-18}
BBR chamber	5006.3	6.4
BBR oven	0.5	0.5
Quadratic Zeeman	747.3	5.3
Lattice	-2.0	4.1
Collisions	0.0	3.8
Background gas	3.8	3.8
DC Stark	0.016	0.016
Probe Stark	0.0	1.0
Servo Error	0.0	0.0
Total Correction	5755.9	10.8
Gravitational redshift	-1215.0	2.7
Total including gravitational redshift	4540.9	11.1

Table 2: Uncertainty budget of the NPL-Sr1 lattice clock for this evaluation period. Reported uncertainties correspond to 68% confidence intervals.

This is an improvement compared to the earlier reports covering the periods MJD 57904–57919 and MJD 57929–57934, and results from the use of a more stable laser at 1064 nm to stabilise the 698 nm clock laser. The stability was evaluated by interleaved measurements.

Type B uncertainty

The type B uncertainty u_B is the sum in quadrature of the systematic uncertainty of NPL-Sr1 and the uncertainty of the gravitational redshift relative to the conventionally adopted reference potential $W_0 = 62\ 636\ 856.0\ \mathrm{m^2s^{-2}}$.

The systematic frequency corrections and uncertainty budget for NPL-Sr1 for the period of this report are given in table 2. The geopotential value for NPL-Sr1 is taken from [3].

Changes to the uncertainty evaluation presented in reference [2] are described below. We also note that subsequent to this evaluation, an updated dynamic correction coefficient for blackbody radiation was reported in reference [4]. This would increase the total BBR correction by approximately 4×10^{-18} for our operational conditions at close to 300 K, but we have not revised the uncertainty budget here to account for this.

Quadratic Zeeman

Compared to earlier evaluation periods and reference [2], NPL-Sr1 was operated with a larger mean stretched state splitting, of approximately 1154 Hz rather than 706 Hz. As a consequence the quadratic Zeeman shift correction is larger. In addition, a dynamically varying correction is applied to the data, meaning that the uncertainty is dominated by the uncertainty in the shift coefficient, whereas previously a contribution from the variation in the measured line splitting also had to be accounted for.

Background gas

For this evaluation we use an updated coefficient for the background gas collisional shift of $(-3.0 \pm 0.3) \times 10^{-17}/\tau$, where τ is the $1/e$ vacuum-limited trap lifetime [5]. Assuming hydrogen is the dominant gas in our system we arrive at a shift of -3.8×10^{-18} based on lattice trapped lifetime measurements of 8 s. However, since the gas composition is only assumed, and the lifetime measurement may be reduced by parametric heating in the lattice trap, we assign an uncertainty equal to the shift.

Collisions

In August 2018, a lattice enhancement cavity was implemented on NPL-Sr1. As a result, the trapping waist is considerably larger than in reference [2] and previous evaluation periods (153 μm compared to 65 μm). The shift due to cold collisions is therefore expected to be lower than previously, but the uncertainty is conservatively estimated to be the same as before.

Lattice

A full re-evaluation of the lattice shift following implementation of the optical cavity was completed for the reported evaluation period and followed the approach and coefficients set out in reference [2]. The total scalar/tensor shift was determined to be $(1.2 \pm 3.2) \times 10^{-18}$ and the higher order hyperpolarisability and E2/M1 shift was $(0.8 \pm 2.5) \times 10^{-18}$.

3 Frequency comparison

Type A uncertainty

The uncertainty $u_{\mathrm{A/Lab}}$ arises from the dead time in the comparison between UTC(NPL) and NPL-Sr1, and includes both a deterministic correction due to maser drift and a stochastic contribution (table 3).

Contribution	Uncertainty / 10^{-18}
$u_{\mathrm{A/Lab}}$[Deterministic]	25
$u_{\mathrm{A/Lab}}$[Stochastic]	365
$\boldsymbol{u_{\mathrm{A/Lab}}}$**[Total]**	366

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

The stochastic contribution was estimated by a method described in reference [6]. This involves a Monte-Carlo approach where the frequency noise of UTC(NPL) is simulated and a value calculated for the offset between the mean frequency during the uptime periods and the mean frequency during the whole evaluation period. The simulation was repeated 1000 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-Sr1. The maser noise model used comprised white phase noise of $4 \times 10^{-13}/\tau$, white frequency noise of $12 \times 10^{-14}/\sqrt{\tau}$, and a flicker frequency floor of 0.8×10^{-15}. These values were derived from measurements of UTC(NPL) by NPL-Sr1.

For this evaluation period, NPL-Sr1 had an uptime of 49.2%, distributed as shown in figure 1.

Figure 1: Uptime of NPL-Sr1 over the evaluation period (green regions).

Type B uncertainty

The uncertainty $u_{\mathrm{B/Lab}}$ is dominated by the distribution of the 10 MHz signal from the maser generating UTC(NPL) 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 [2], and their contribution to the uncertainty estimated from the instability of these fluctuations over the evaluation period.

References

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