# Frequency evaluation of UTC(NPL) by NPL-Sr1
# for the period MJD 58659 to MJD 58679

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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 20 days from MJD 58659 to MJD 58679 (25th June 2019 – 15th July 2019). The Sr optical lattice clock operation covers 71.1% 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$^2$ $^1$S$_0$ – 5s5p $^3$P$_0$ 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) /$10^{-16}$ | $u_{\mathrm{A}}$ /$10^{-16}$ | $u_{\mathrm{B}}$ /$10^{-16}$ | $u_{\mathrm{A/Lab}}$ /$10^{-16}$ | $u_{\mathrm{B/Lab}}$ /$10^{-16}$ | $u_{\mathrm{Srep}}$ /$10^{-16}$ | Uptime |
|---|---|---|---|---|---|---|---|
| MJD 58659–58679 | 1.57 | 0.005 | 0.10 | 1.46 | 1.12 | 1.9 | 71.1% |

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 $5 \times 10^{-16}/\sqrt{\tau}$, extrapolated to the duration of the evaluation period.

| Systematic effect | Correction / $10^{-18}$ | Uncertainty / $10^{-18}$ |
|---|---|---|
| BBR chamber | 4875.0 | 5.0 |
| BBR oven | 0.5 | 0.5 |
| Quadratic Zeeman | 765.0 | 1.0 |
| Lattice | 5.8 | 3.0 |
| Collisions | 0.0 | 3.8 |
| Background gas | 5.3 | 5.3 |
| DC Stark | 0.016 | 0.016 |
| Probe Stark | 0.0 | 1.0 |
| Servo Error | 0.0 | 0.0 |
| **Total Correction** | 5651.6 | 8.9 |
| Gravitational redshift | -1215.0 | 2.7 |
| **Total including gravitational redshift** | 4436.6 | 9.3 |

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 58454–58459 ($8 \times 10^{-16}/\sqrt{\tau}$) and MJD 57904–57919 and MJD 57929–57934 ($2 \times 10^{-15}/\sqrt{\tau}$). The improvement is a direct result of improvements made to the 1064 nm laser to which the 698 nm clock laser is stabilised. 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 $W_0 = 62\ 636\ 856.0\ \mathrm{m}^2\mathrm{s}^{-2}$.

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].

The uncertainty in table 2 is lower than that of the uncertainty evaluation published in reference [2]. For this reason, the value of $u_B$ in table 1 is increased to the published value that has undergone peer review.

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 $4 \times 10^{-18}$ for our operational conditions at close to 300 K, but we have not revised the uncertainty budget here to account for this.

### *Quadratic Zeeman*

As for the evaluation period MJD 58454–58459, NPL-Sr1 was operated with a larger mean stretched state splitting compared to earlier evaluation periods and reference [2]. 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.

A further change in this evaluation report is the use of an updated value with reduced uncertainty for the quadratic Zeeman shift coefficient, of $-2.456(3) \times 10^{-7}$ Hz$^{-1}$ [5].

### *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 $\tau$ is the $1/e$ vacuum-limited trap lifetime [6]. Assuming hydrogen is the dominant gas in our system we arrive at a shift of $-5.3 \times 10^{-18}$ based on lattice trapped lifetime measurements of 5.7 s (re-evaluated after installation of the lattice enhancement cavity in August 2018). 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] (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 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 $(-6.6 \pm 1.7) \times 10^{-18}$ and the higher order hyper-polarisability 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] | 15 |
| $u_{\mathrm{A/Lab}}$[Stochastic] | 145 |
| **$u_{\mathrm{A/Lab}}$[Total]** | 146 |

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

The stochastic contribution was estimated by a method described in reference [7]. 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 $4 \times 10^{-13}/\tau$,

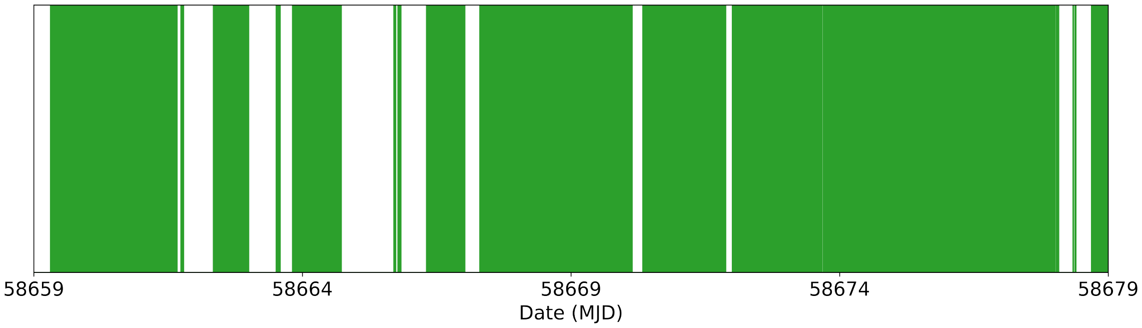

Figure 1: Uptime of NPL-Sr1 over the evaluation period (green regions).

white frequency noise of $12 \times 10^{-14}/\sqrt{\tau}$, and a flicker frequency floor of $0.8 \times 10^{-15}$. These values were derived from measurements of UTC(NPL) by NPL-Sr1.

For this evaluation period, NPL-Sr1 had an uptime of 71.1%, distributed as shown in figure 1.

### 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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