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Optically steered time scale generation at OP and NPL and remote comparisons

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Abstract. In this paper, we present real-time optically steered time scales generated simultaneously at the Observatoire de Paris (OP) and the National Physical Laboratory (NPL). Throughout one month, experimental UTCx(*k*) time scales were generated concurrently in the two laboratories alongside the local operational UTC(*k*) time scales. The UTCx(*k*) time scales were based on hydrogen masers whose frequencies were calibrated by local optical frequency standards using optical frequency combs, with algorithms being developed for outlier filtering and frequency steering estimations in the two laboratories. The performance of the experimental time scales was assessed through local comparisons against the corresponding UTC(*k*) time scales, and also through remote comparisons performed both via Coordinated Universal Time (UTC) and by using the GPS Precise Point Positioning (PPP) technique. The two optically steered time scales remained within 4 ns of each other, outperforming the corresponding UTC(*k*) over the same period. To our knowledge, this is the first reported comparison of two independent “optical time scale” prototypes, and the results demonstrate the capability of optical clocks to produce operational time scales.

1. Introduction

Optical frequency standards (OFS) under development in many institutions worldwide have demonstrated impressive progress in terms of accuracy and stability [1–5], surpassing the performance of atomic fountain microwave frequency standards by two orders of magnitude. In the context of the anticipated redefinition of the second in the International System of units (SI) [6], several OFS currently considered as secondary representations of the SI second are already contributing to the steering of International Atomic Time (TAI), calculated monthly by the Bureau International des Poids et Mesures (BIPM). Local time scales maintained by National Metrology Institutes will also benefit from the accuracy and stability of OFS, which are expected to enable the time offset of these UTC(*k*) time scales (where *k* refers to the institute) from Coordinated Universal Time (UTC) to be maintained in the 100 ps range or lower [7–10].



In this paper, we present real-time optically steered time scales generated simultaneously at the Observatoire de Paris (OP) and the National Physical Laboratory (NPL). In this experiment, performed during the Robust Optical Clocks for International Timescales (ROCIT) project [11], independent experimental time scales $UTCx(k)$ were generated concurrently for one month in the two laboratories in parallel to the local operational $UTC(k)$ time scales. The experimental $UTCx(k)$ time scales were based on hydrogen masers whose frequency was calibrated by the local OFS (SYRTE-SrB and SYRTE-Sr2 optical lattice clocks [12] at OP, NPL-Sr1 strontium optical lattice clock [13] and NPL-E3Yb+3 ytterbium ion optical clock [14] at NPL) via optical frequency combs. From these frequency calibrations, steering corrections were updated on an hourly basis via frequency offset generators (FOGs), to compensate for the real time maser frequency fluctuations more frequently than in the local $UTC(k)$ time scales, where steering parameters are typically updated with a periodicity of one or a few days. After describing the experimental measurement chains, we present the algorithms that were implemented for outlier filtering and frequency steering estimations. We then analyse the performance of the experimental time scales based firstly on local comparison against the local $UTC(k)$ and secondly on remote comparisons performed via UTC and using the GPS Precise Point Positioning (PPP) technique, before outlining strategies for improvement. Further details will be available in a publication in preparation.

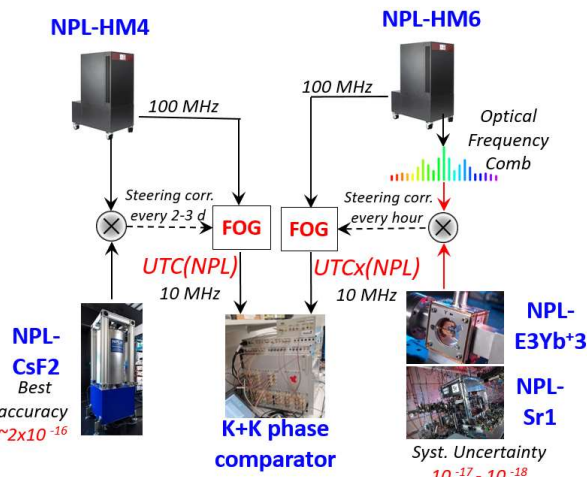


Figure 1. Experimental setup implemented at NPL

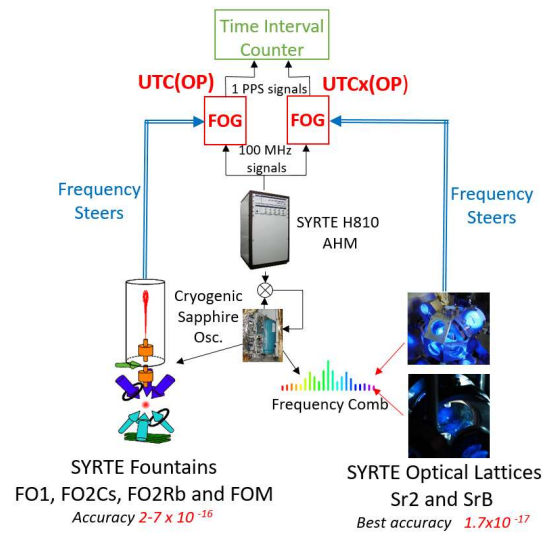


Figure 2. Experimental setup implemented at OP

2. NPL optically steered time scale: $UTCx(NPL)$

At NPL an optical lattice clock based on the $5s^2 \ ^1S_0$ to $5s5p \ ^3P_0$ transition in ^{87}Sr (labelled as NPL-Sr1) [13] and a trapped ion optical clock based on the $^2S_{1/2} \rightarrow ^2F_{7/2}$ electric octupole transition in $^{171}\text{Yb}^+$ (labelled as NPL-E3Yb+3) [14, 15] were operated during an international clock comparison campaign in March 2022. During this period, both optical clocks were used to steer a local microwave flywheel oscillator (active hydrogen maser NPL-HM6) in order to realise a prototype optical time scale. Figure 1 shows a simplified scheme of the experimental setup of $UTCx(NPL)$ where the output frequency from the maser is up-converted to the optical domain using a fibre-based optical frequency comb (OFC) and then compared to the frequencies of the two optical clocks.

The frequency of the optical clocks compared against NPL-HM6 is measured by the OFC with a sampling time of 1 s and validated in hour-long chunks. The optical clock data is also validated in real time, with on-the-fly correction of the systematic frequency shifts. From the validated comparison data,

we derive the fractional frequency difference (FFD) $y[X - \text{HM6}]$ between the optical clocks and NPL-HM6 where X is either NPL-Sr1 or NPL-E3Yb+3. The computed FFD is used to steer the flywheel by means of a FOG. The steering parameter is updated every hour according to the following scenarios:

- If both optical clocks provide data for at least 25% of the hour, the averaged FFD $y[X - \text{HM6}]$ values from each clock are combined via a weighted mean, with weights proportional to the relative proportion of available data.
- If only one optical clock is available within the hour, its averaged FFD is used.
- If neither clock provides sufficient data, then past steering parameters and the frequency drift of NPL-HM6 are used to predict the steering parameter.

An assessment of the stability of the prototype UTCx(NPL) time scale is enabled through a comparison with the local UTC(NPL) time scale. A simplified scheme of the generation of UTC(NPL) is also shown in Figure 1; it is based on another active hydrogen maser (NPL-HM4) whose frequency is steered by the NPL caesium fountain primary frequency standard (NPL-CsF2) [16,17]. A phase comparator is used to measure the phase difference between UTCx(NPL) and UTC(NPL).

During the one month experiment, the offsets of UTCx(NPL) from UTC, computed using the local measurement $\text{UTCx(NPL)} - \text{UTC(NPL)}$ and data from Circular T, remained within ± 0.64 ns. This is significantly better than the operational UTC(NPL) time scale, which differed from UTC by as much as 2.7 ns over the same period. One limiting factor to the operation of UTCx(NPL) was the appearance of a few phase jumps in the resulting time scale. These glitches were identified as being due to two main problems: firstly the FOG would occasionally add an instantaneous phase jump when a frequency steer was applied, and secondly invalid data occasionally passed through our filters. Both types of glitches were rapidly apparent from the comparison between UTCx(NPL) and UTC(NPL), making it possible to correct for these erroneous phase offsets in-situ.

3. OP optically steered timescale: UTCx(OP)

At OP, we operated an experimental time scale UTCx(OP) based on combining data from the two strontium optical lattice clocks SYRTE-Sr2 and SYRTE-SrB [12] during the measurement campaign performed in March 2022 and compared it to our operational local time scale UTC(OP). The experimental setup is shown in Figure 2. The frequency reference of the laboratory is based on the active hydrogen maser 1400810 filtered by a cryogenic sapphire oscillator (CSO) presenting an excellent short term stability. The resulting hybrid oscillator provides a signal at 11.98 GHz that is compared to the two optical clocks via an OFC, and also feeds the microwave synthesizer of the OP caesium and rubidium atomic fountains (FO1, FO2Cs, FO2Rb and FOM) [18, 19].

UTC(OP) is generated using a frequency offset generator (FOG) developed by SKK Electronics [20] to steer a 100 MHz signal from the hydrogen maser. More details on the generation of UTC(OP) can be found in [21]. During this experiment, UTCx(OP) was generated using a second FOG to steer the same reference maser. The steering algorithm uses as input the 1 s sampled maser – SrX data (SrX = SYRTE-Sr2 and SYRTE-SrB, respectively), corrected for the strontium systematic frequency shifts and made available in real time. There is no additional steering towards UTC.

The steering correction is calculated every hour. After outlier filtering of the maser – SrX data, we compute a “pack” of data averaged over periods of $0.1d$ for each OFS. We also compute extrapolated values using the available pack data of both OFS during the previous $5d$ with respect to the time of the computation correction. The steering is updated to the FOG every hour according to the following approach: if the last pack is older than $0.4d$, we take the last extrapolated value for the new steering, otherwise, we take the last valid pack data. If the difference between the previous steering and the new one is larger than 2×10^{-14} , the steering is considered as an outlier and thus not updated.

The experimental time scale UTCx(OP) was compared to UTC(OP) using a time interval counter and to UTC using Circular T data. Both differences $\text{UTCx(OP)} - \text{UTC(OP)}$ and $\text{UTCx(OP)} - \text{UTC}$ remained below 2 ns during the entire duration of the campaign, while UTC(OP) was no more than 0.5 ns away from UTC over the period. As at NPL, the time scale prototype at OP was affected by phase jumps due to bad outlier rejection. This led to incorrect steering in four instances during the month.

If we ignore the anomalous steering events, the time scale showed its potential to remain within a few hundred ps of UTC over the one-month period. In order to demonstrate this, we performed simulations with the same algorithm using maser – SrX data after a manual filtering of the outliers. The simulations were performed using Sr2 and SrB independently for comparison purposes. The accumulated phase of the simulated time scale UTCxSrB with respect to UTC remained below 600 ps over the 30d period. It was a bit larger (1.2 ns) for UTCxSr2 due to the effect of missing data close to the end of the period.

4. Distant comparison of the independent timescale prototypes

To compare the experimental time scales, we combined the local UTCx(k) – UTC(k) comparisons with UTC(NPL) – UTC(OP) comparisons performed both via UTC and using the GPS Precise Point Positioning (PPP) technique. These comparisons showed that the time scale prototypes remained within 4 ns of each other, with the observed fluctuations dominated by the anomalous events on the two time scales. The different comparison techniques agree to within a few hundred ps. The comparisons of the *a posteriori* corrected time scales resulted in differences lower than 2 ns. This is an improvement by a factor of two with respect to the comparison between the local time scales UTC(NPL) and UTC(OP).

5. Conclusion

In the context of a future redefinition of the second [6], this paper presents one of the first attempts to generate real-time optically steered time scales. NPL and OP demonstrated the first out-of-loop comparison of two independent time scales steered exclusively with optical clock data that exhibited a lower difference than for that of the corresponding operational UTC(k) time scales over the same period. The results of the experiment were affected by a few phase jumps due to data validation issues and unexpected behaviour of the FOGs used for steering. Correction of these issues in post processing showed a factor of two improvement in time deviation over the period with respect to the local UTC(k) comparison.

This result shows the potential of using OFS for the generation of highly accurate time scales. Further work is ongoing at NPL and OP, as well as in other institutions, towards increasing the reliability of operation of the optical clocks and measurement chains, improving the steering algorithms and testing optically-steered time scale prototypes over much longer periods.

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References

- [1] Ushijima I, Takamoto M, Das M, Ohkubo T and Katori H 2015 Cryogenic optical lattice clocks *Nature Photonics* **9** 185-189
- [2] Huntemann N, Sanner C, Lipphardt B, Tamm Chr and Peik E 2016 Single-ion atomic clock with 3×10^{-18} systematic uncertainty *Phys. Rev. Lett.* **116** 063001
- [3] McGrew W *et al.* 2018 Atomic clock performance enabling geodesy below the centimetre level *Nature* **564** 87-90
- [4] Bothwell T, Kedar D, Oelker E, Robinson J M, Bromley S L, Tew W L, Ye J and Kennedy C J 2019 JILA SrI optical lattice clock with uncertainty of 2.0×10^{-18} *Metrologia* **56** 065004
- [5] S. Brewer, Chen J S, Hankin A M, Clements E R, Chou C W, Wineland D J, Hume D B and Leibrandt D R 2019 $^{27}\text{Al}^+$ quantum-logic clock with a systematic uncertainty below 10^{-18} *Phys. Rev. Lett.* **123** 033201
- [6] Dimarcq N *et al* 2024 Roadmap towards the redefinition of the second *Metrologia* **61** 012001
- [7] Formichella V, Galleani L, Signorile G and Sesia I 2021 Robustness tests for an optical time scale *Metrologia* **59** 015002

- [8] Grebing C, Al-Masoudi A, Dörscher S, Häfner S, Gerginov V, Weyers S, Lipphardt B, Riehle F, Sterr U and Lisdat C 2016 Realization of a timescale with an accurate optical lattice clock *Optica* **3** 563–569
- [9] Hachisu H, Nakagawa F, Hanado Y and Ido T 2018 Months-long real-time generation of a time scale based on an optical clock *Scientific Reports* **8** 4243
- [10] Yao J *et al.* 2019 Optical-clock-based time scale *Phys. Rev. App.* **12** 044069
- [11] Margolis H S *et al.* 2024 Robust optical clocks for international timescales (ROCIT) in *this proceedings*
- [12] Lodewyck J *et al.* 2016 Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock *Metrologia* **53** 1123
- [13] Hobson R, Bowden W, Vianello A, Silva A, Baynham C F A, Margolis H S, Baird P E G, Gill P and Hill I R 2020 A strontium optical lattice clock with 1×10^{-17} uncertainty and measurement of its absolute frequency *Metrologia* **57** 065026
- [14] Nisbet-Jones P B R, King S A, Jones J M, Godun R M, Baynham C F A, Bongs K, Doležal M, Balling P and Gill P 2016 A single-ion trap with minimized ion-environment interactions *Applied Physics B* **122** 57
- [15] Godun R, Nisbet-Jones P, Jones J, King S, Johnson L, Margolis H, Szymaniec K, Lea S, Bongs K and Gill P 2014 Frequency ratio of two optical clock transitions in $^{171}\text{Yb}^+$ and constraints on the time variation of fundamental constants *Phys. Rev. Lett.* **113** 210801
- [16] Szymaniec K, Park S E, Marra M and Chalupeczak W 2010 First accuracy evaluation of the NPL-CsF2 primary frequency standard *Metrologia* **47** 363
- [17] Li R, Gibble K and Szymaniec K 2011 Improved accuracy of the NPL-CsF2 primary frequency standard: evaluation of distributed cavity phase and microwave lensing frequency shifts *Metrologia* **48** 283
- [18] Guéna J *et al.* 2012 Progress in atomic fountains at LNE-SYRTE *Trans. Ultrason. Ferroelectr. Freq. Control* **59** 391
- [19] Guéna J, Abgrall M, Clairon A and Bize S 2014 Contributing to TAI with a secondary representation of the SI second *Metrologia* **51** 108
- [20] Rovera G D, Abgrall M and Siccaldi M 2012 Characterization of an auxiliary offset generator for steering of H Masers *Proc. 2012 EFTF* 14–15
- [21] Rovera G D, Bize S, Chupin B, Guéna J, Laurent P, Rosenbusch P, Urich P and Abgrall M 2016 UTC(OP) based on LNE-SYRTE atomic fountain primary frequency standards *Metrologia* **53** S81