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Robust Optical Clocks for International Timescales (ROCIT)

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Abstract. The recently concluded collaborative European project "Robust optical clocks for international timescales" (ROCIT) tackled some of the key challenges on the roadmap towards a redefinition of the SI second. This paper gives an overview of progress made on improving the robustness and automation of optical clocks and verifying their uncertainty budgets through coordinated international comparison campaigns. It also presents work on the incorporation of optical clocks into time scales, covering both their use to steer local physical time scales and their use for evaluations of hydrogen masers contributing data for the computation of International Atomic Time (TAI). The overall objective of the project was to bring European optical clocks to the stage where they could be operated routinely as secondary frequency standards, regularly contributing to TAI.

1. Introduction

Due to the unprecedented stability and accuracy achievable with optical atomic clocks, which now surpass the performance of the best caesium microwave primary frequency standards by up to two orders of magnitude, an optical redefinition of the second is anticipated. The Consultative Committee for Time and Frequency (CCTF) has prepared a detailed roadmap [1], which sets out the key challenges that remain to be addressed before the redefinition can be implemented, along with a set of criteria that enables an assessment to be made of readiness for the change. These criteria are separated into mandatory criteria that must be met before changing the definition, and ancillary conditions that should be well advanced by the time of the redefinition but that do not necessarily need to be completely achieved.

The overall aim of the "Robust optical clocks for international timescales" (ROCIT) project was to bring European optical clocks to the stage where they can contribute regularly to International Atomic Time (TAI) as secondary frequency standards. A key enabler for the use of optical clocks in time scales is improvement to their robustness and automation, making this the initial area of focus for the project consortium (section 2) even though high reliability of optical frequency standards is one of the ancillary conditions in the roadmap towards redefinition. Significant effort was also devoted to validation of the uncertainty budgets of the optical clocks through a programme of international comparisons (section 3), which also addressed the mandatory criterion of continuity with the present definition of the second. Section 4 focuses on progress towards the incorporation of optical clocks into UTC(k) timescales, the physical realisations of UTC maintained by national timing laboratories, while section 5 covers optical clock contributions to TAI. Conclusions and future prospects are presented in section 6.

2. Robustness and automation of optical clocks

Within the ROCIT project, advances were made in the robustness and automation of both trapped ion optical clocks and neutral atom optical lattice clocks, with the focus on the systems that were known to require most frequent user intervention.

Developments included new approaches for automatic long-term control of laser systems and for automated adjustment of optical setups. For example, methods were developed for automatically relocking lasers to external stabilisation cavities, external enhancement cavities used for second-harmonic generation and enhancement cavities for optical lattices. Systems were also developed for automatic laser beam alignment into optical fibres and alignment of objectives for ion imaging.

Another area of work, the priority of which was emphasized by the COVID-19 pandemic, was the development of systems for remote monitoring and control. It is now possible to diagnose, and in many cases rectify, many common problems without entering the laboratory, making running extended measurement campaigns far less arduous than in the past. Some of the software developed for this purpose has been published as open source on GitHub, for example tools for remote monitoring and locking lasers using a commercial wavemeter [2] and for almost real-time monitoring of the blackbody radiation shift in an optical lattice clock [3]. Routines to recover automatically from certain erroneous clock states were also developed, although for most systems some error conditions still require human intervention. In most such cases, an alert system has been implemented to inform operators of the error condition, supporting the minimisation of downtime.

A range of software was also developed to schedule and perform key operational checks, and to determine through interleaved measurements the magnitude of the environmental parameters that cause frequency shifts. For example, routines developed for ion-based clocks included ion loading, minimisation of residual electric fields via measurement of ion micromotion, and minimisation of magnetic fields via measurement of the Zeeman components of the clock transition.

Based on these developments, LNE-SYRTE, NPL and PTB were all able to demonstrate unattended optical clock operation with uptimes exceeding 80 % over 2 weeks for at least one of their optical clocks. In all cases the remaining downtime was dominated by a few longer interruptions to operation, and further engineering improvements are envisaged to address their causes.

3. International consistency of optical clocks

The mandatory criteria set out in the roadmap towards the redefinition of the second include the validation of optical clock uncertainties through the comparison of systems developed independently in different laboratories around the world, with the numerical target for comparison uncertainties set at 5 parts in 10^{18}. With this objective in mind, the ROCIT project included an extensive programme of optical clock comparisons, including both local and remote measurements (Figure 1). This programme involved two new optical clocks that were completed and operated for the first time as part of the project: the $^{88}Sr^+$ optical clock at VTT MIKES [4] and the $^{115}In^+$ optical clock at Leibniz University Hannover/PTB. In addition, the ^{88}Sr optical lattice clock in Toruń joined international comparisons for the first time as part of the project and data was shared from the new $^{88}Sr^+$ optical clock at PTB [5].

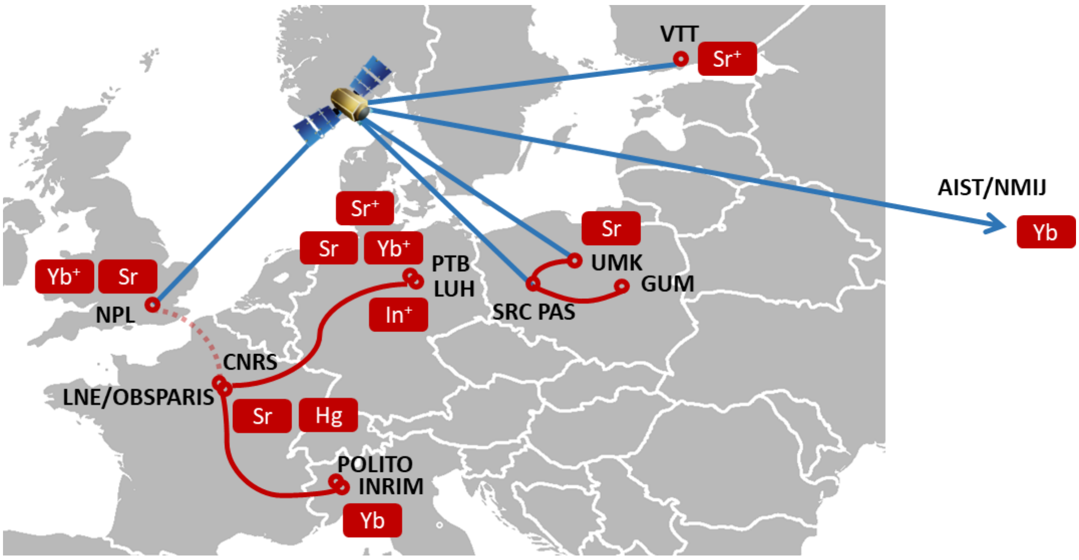

Figure 1. Optical clocks (red boxes) and laboratories involved in the ROCIT optical clock comparison programme, which included both local and remote comparisons. NMIJ joined the programme as a collaborator with the European consortium. The red lines indicate optical fibre links between laboratories (the link between NPL and LNE/OBSPARIS is dotted because it could not be used in the March 2022 campaign due to an unplanned interruption). The blue lines indicate the laboratories that could only be linked by GNSS time and frequency transfer.

3.1. Remote clock comparisons
Currently the only way to link optical clocks in different locations and reach comparison uncertainties that are comparable to the estimated uncertainties of the clocks themselves is by transmission of an optical carrier signal over a specially configured, phase-coherent optical fibre link. Where suitable infrastructure exists, this is therefore the technology of choice for remote optical clock comparisons.

During the ROCIT project, a new optical fibre link was completed between Paris and Turin [6], to extend the reach of the pre-existing European optical clock network linking LNE-SYRTE, NPL and PTB [7, 8] and allow the ^{171}Yb optical lattice clock at INRIM to join international comparisons by fibre link for the first time. Comparisons using this network benefit from the European quasi-geoid model computed as part of an earlier European project, "International Timescales with Optical Clocks" (ITOC) [9], which incorporated new gravity measurements carried out at and around the NMI sites [10, 11]. That prior work unified the description of the geopotential for European NMIs and the uncertainty in the knowledge of the local geopotential at the four NMIs linked by the network meets the numerical target in the roadmap towards definition.

Two coordinated programmes of frequency comparisons were carried out during the project. The first, planned for March 2020, was badly disrupted by the COVID-19 pandemic. The second, performed in March 2022, was far more successful, involving eleven optical clocks in seven different countries, including one from outside Europe (the ^{171}Yb optical lattice clock at NMIJ in Japan). To maximise the number of laboratories that could participate, satellite-based techniques were used in addition to the optical fibre network.

A detailed description of this campaign and the results obtained are being prepared for publication elsewhere, so only an outline is provided here. In total 27 frequency ratios between remote optical clocks were measured, with the comparisons via fibre link reaching uncertainties in the low parts in 10^{17} range while the comparisons via satellite link were limited to the low parts in 10^{16} range. When compared with the 2021 CIPM recommended frequency values for secondary representations of the second, two groups of outliers were observed. The first group of outliers involves the ^{115}In$^+$ optical clock, but in this case the offset is well within the uncertainty in the recommended frequency value, which is determined from earlier less accurate measurements of other ^{115}In$^+$ optical clocks. We thus expect that the new measurements will have a strong influence on the next update to this recommended frequency value. The other group of outliers involves the new ^{88}Sr$^+$ trapped ion optical clock at VTT, and in this case the offset is statistically significant. However, the ratios involving the VTT clock agree with recent results from other ^{88}Sr$^+$ optical clocks [5, 12], in particular the only optical ratio involving ^{88}Sr$^+$ that has so far been published [5]. It therefore seems likely that the problem lies with the recommended frequency value rather than the VTT clock.

3.2. Local clock comparisons
The remote comparisons were supplemented by local optical frequency comparisons. Local optical frequency ratio measurements provide a way to perform consistency checks without the need for a physical link between locations, if the same ratio is measured independently in different laboratories. Such measurements enabled the European optical clocks to be compared with those on other continents, even though no highly stable and accurate links are yet available over such long distances. Traceability to the SI second was ensured by including caesium primary frequency standards in the comparison programme. As identified in the roadmap towards redefinition, absolute frequency measurements of the optical standards at the limit set by the caesium primary standards are essential to avoid any discontinuity occurring at the time of the redefinition.

During the project, 51 local clock comparisons were performed between clocks on the same site. These included 33 absolute frequency measurements, 26 of which were made using local caesium fountain primary frequency standards and seven of which were performed using TAI as the reference. In most cases, the uncertainties in the absolute frequencies were dominated by the reference to the SI second. The local clock comparisons also included 15 optical frequency ratio measurements, several of which had never been determined directly before, and three frequency ratio measurements

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involving the rubidium fountain secondary frequency standard at LNE-SYRTE. Most of the local optical frequency ratio measurements achieved uncertainties in the low parts in 10^{17} range. Some local frequency comparison results have already been published [5, 13–17], whilst others are still being finalised for publication.

These local measurements, together with the remote frequency comparison results, will greatly augment the body of high-accuracy clock comparison data available worldwide, with uncertainties being reduced by up to an order of magnitude in some cases. Correlation coefficients between the different measurements were also computed, to feed into future updates to the CIPM recommended values of standard frequencies (section 5.1).

4. Optical clocks in UTC(*k*) time scales

4.1. Real-time data validation and on-the-fly correction of systematic frequency shifts

Essential prerequisites for using optical clocks to steer UTC(*k*) time scales are the ability to validate the clock data in real time and to evaluate and correct for systematic frequency shifts at an appropriate level on the fly.

Our work on real-time data validation considered the whole metrological connection between the optical reference and the hydrogen maser flywheel used to generate the time scale, including the frequency combs and any local optical fibre links as well as the optical clocks themselves. Techniques used included cycle slip detection in frequency comb measurements by redundant counting, algorithms for detecting sudden unexpected changes in frequency measurements, and the setting of a threshold level for validation of atom number in optical lattice clocks.

Experimental control systems were extended to perform on-the-fly evaluation and correction of systematic frequency shifts by developing routines to measure the magnitude of residual frequency shifting parameters and to store the data acquired in a database for subsequent use by shift calculation routines. For example, residual magnetic fields are monitored via the Zeeman splitting of atomic states, while the blackbody radiation shift is derived from accurate monitoring of the thermal environment using temperature sensors. Residual electric fields in trapped ion clocks are monitored by measuring the ion micromotion.

These developments enabled LNE-SYRTE, NPL and PTB each to demonstrate on-the-fly evaluation and correction of systematic frequency shifts in at least one of their optical clocks. These advances are beneficial not only for real-time steering of UTC(*k*) time scales, but also for faster analysis of data from clock comparison campaigns (section 3) and for low latency contributions of optical clock data to TAI (section 5.2).

4.2. Steering algorithm development

While microwave clocks used to steer UTC(*k*) time scales typically operate with an uptime close to 100 %, most optical clocks do not yet achieve this level of reliability, even though they have better stability and accuracy. This means that steering algorithms used with optical clocks must be able to handle lower data availability.

Two independent steering algorithms were designed to adapt to these conditions. The first addressed the effect of gaps in the optical clock data and was adapted to be able to handle low uptimes and long periods of data unavailability [18]. Using simulated optical clock data, it was demonstrated that in the ideal scenario of continuous optical clock operation, the fluctuations of the time scale can be maintained within a few hundred picoseconds even if the steering corrections are applied only once per day. With the optical clock operation reduced to one 24-hour period per week, the fluctuations remain within several nanoseconds, close to the best conventionally steered time scales available today.

A second algorithm was tailored to adapt to possible lags between data acquisition and correction, as well as to unexpected changes of the frequency drift of the flywheel. Tests of this algorithm showed that, with typical fluctuations in maser flywheel drift, time scale fluctuations could be maintained at the nanosecond level with a lag of one day in data availability, but that higher latency can rapidly lead to excursions of several tens of nanoseconds.

4.3. Prototype UTC(k) steering using optical clocks

The automated procedures for real-time data validation and on-the-fly correction of systematic frequency shifts (section 4.1), together with the lessons learned from the algorithm testing (section 4.2) were exploited to realise experimental prototypes of optically steered time scales, which we refer to as UTCx(k).

During the March 2022 international clock comparison campaign, two prototype time scales UTCx(NPL) and UTCx(OP) were independently and simultaneously demonstrated at NPL and LNE-SYRTE, in each case using data from two local optical clocks that achieved high uptimes. The approach was similar to that used to steer the operational UTC(NPL) and UTC(OP) time scales using caesium primary frequency standards, with a frequency offset generator connected to a hydrogen maser flywheel being steered using data from the local optical clocks. The difference lies in the interval between steers being applied. For example, at NPL caesium-fountain-based steers are applied three times a week, while the interval between optical clock steers was reduced to one hour.

Despite a few data validation issues and technical issues with the frequency offset generators used for steering of the hydrogen maser flywheels, both UTCx(k) time scales remained less than 2 ns away from UTC over the 30 days of the test. The two UTCx(k) time scales were also compared directly via a satellite-based time transfer link, with their offset found to remain smaller than the offset between the corresponding operational UTC(k) time scales over the same period.

A more detailed description of this experiment is being prepared for separate publication.

5. Optical clocks in TAI

Incorporation of optical clocks into the global time scale as secondary representations of the second is achieved by comparing the optical clocks with hydrogen masers that are used in the computation of TAI and submission of this frequency comparison data to the BIPM for inclusion in the monthly bulletin Circular T. While the definition of the SI second is still based on the ground state hyperfine transition in ^{133}Cs, optical clocks may only contribute to TAI with the uncertainty of the recommended frequency value for the secondary representation of the second.

5.1. Optimised frequency values for secondary representations of the second

The recommended values of these standard frequencies are computed by the CCL-CCTF Frequency Standards Working Group (WGFS) [19], based on the worldwide body of clock comparison data. Since 2015, this has been done using least-squares analysis methods developed within the aforementioned ITOC project [20].

The most recent update to the list, approved by the CCTF in March 2021, differed in one crucial respect from previous adjustments performed in 2015 and 2017 [21]. For the first time, detailed consideration was given to correlations between the individual frequency measurements to ensure that the recommended frequency values derived from the data are unbiased and that their uncertainties are not underestimated. This change was influenced by work performed within the ROCIT project, in particular our guidelines on the evaluation and reporting of correlation coefficients [22]. Correlations arise from various sources, with the most significant being correlations from the use of the same primary or secondary frequency standard to access the SI second and correlations between different measurements performed within the same coordinated comparison campaign.

The new recommended values for standard frequencies were used for the first time for the calculation of TAI in Circular T no. 412 (April 2022). From that point, optical clocks have been able to steer TAI with lower uncertainty, as the recommended frequency values for the two types currently contributing (strontium and ytterbium optical lattice clocks) both now have uncertainties at the limit set by caesium fountain primary frequency standards. The update thus resulted in a significant increase in the weight of optical clocks in TAI (Figure 2).

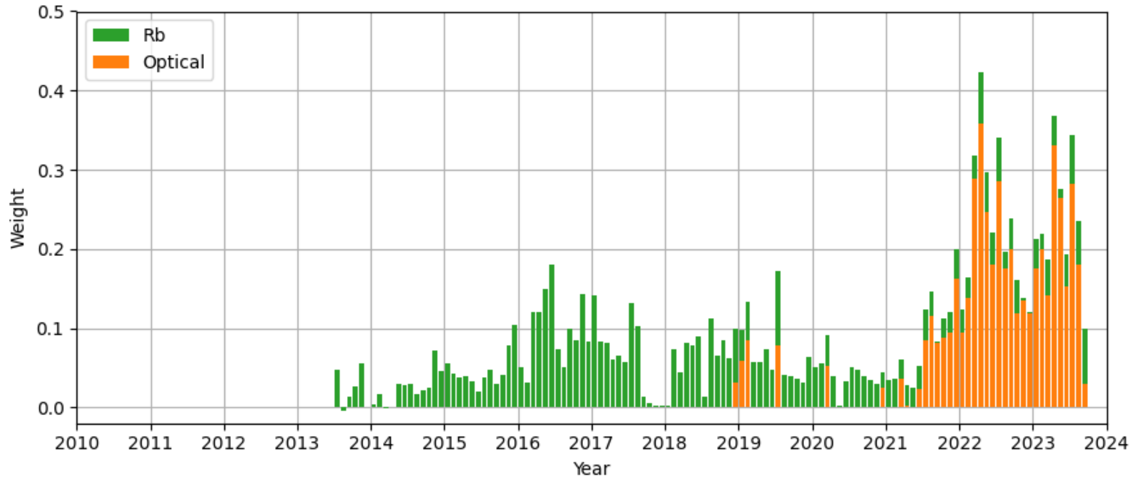

Figure 2. Graphical representation of the weights of secondary representations of the second in TAI, separated into the contributions from Rb and optical clocks, based on data published at https://www.bipm.org/en/time-ftp/other-products ("Fractional frequency of EAL from primary and secondary frequency standards").

5.2. Optical clock contributions to TAI

During the ROCIT project, twelve optical clocks within the consortium were used to evaluate the frequency of hydrogen masers contributing to the computation of TAI, with measurement periods aligned with the 5-day reporting periods of Circular T. A total of 55 periods ranging from 5 to 35 days were recorded during the project, representing a total cumulative data acquisition period exceeding 1000 days.

Five contributions from the SYRTE optical lattice clock SYRTE-Sr2 were used for TAI steering in 2021 and 2022, with one further contribution made in early 2023.

The INRIM ^{171}Yb optical lattice clock IT-Yb1 received approval from the CCTF Working Group on Primary and Secondary Frequency Standards (WGPSFS) in November 2019 and the submitted data was used for TAI steering that month. From February 2022 to May 2023 it contributed monthly to Circular T, a total of 16 contributions, and had the highest weight of any clock in TAI in July 2022.

The first data from NPL's ^{87}Sr optical lattice clock NPL-Sr1 was submitted to the BIPM in December 2022 and following approval by the WGPSFS was used for TAI steering in March 2023. By the time of the 9th symposium NPL-Sr1 had contributed three evaluations carried out within the month of TAI evaluation.

Data collected from other clocks will be submitted to the BIPM pending updated uncertainty budgets, peer-reviewed publications, and approval by the WGPSFS.

6. Conclusions

The work performed within the ROCIT project has significantly advanced the status of optical clocks within Europe towards meeting some of the key milestones in the international roadmap towards a redefinition of the SI second. The robustness and automation of optical clocks has been significantly improved and the coordinated clock comparison campaigns have greatly expanded the worldwide body of frequency comparison data necessary to validate the uncertainty budgets of these clocks. Methods have been developed for real-time data validation and on-the-fly correction of systematic frequency shifts, paving the way for initial demonstrations of two prototype optically steered UTC(k) time scales and a direct comparison between them.

At the time of the 8th Symposium on Frequency Standards and Metrology in 2015, no optical clocks at all had contributed to TAI. Eight years later, at the 9th Symposium, eight optical clocks in seven different laboratories had been approved by the WGPSFS and had contributed a total of 67 evaluations carried out within the month of TAI evaluation [23]. Of these eight optical clocks, four (SYRTE-Sr2, SYRTE-SrB, IT-Yb1 and NPL-Sr1) are operated by members of the ROCIT consortium, and between them they account for almost 40 % of the "on-time" contributions from optical clocks. This represents significant progress towards the mandatory criterion of regular contributions of optical frequency standards to TAI as secondary representations of the second. However further work is still required to reach the numerical target of at least three state-of-the-art calibrations of TAI each month for at least one year, with uncertainty at or below the 2×10^{-16} level (neglecting the recommended uncertainty of the secondary representation of the second), from a set of at least five optical frequency standards.

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