FINAL PUBLISHABLE REPORT

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1 Overview

Optical atomic clocks have now reached levels of performance that clearly surpass the stability and accuracy achievable with caesium microwave primary frequency standards, with the result that a future optical redefinition of the SI second is anticipated. This project tackled key steps that must be taken prior to the redefinition. The robustness of optical clocks was improved so that they could run unattended for long periods, methods were developed for automatic data validation enabling prototype demonstrations of optically steered timescales, and the long-term reliability and reproducibility of the clocks were assessed through a coordinated programme of international comparisons. By the end of the project several European optical clocks were contributing on a regular basis to International Atomic Time (TAI) as secondary representations of the second, improving its stability and accuracy. These steps represent important progress towards the criteria set out in the international roadmap towards a redefinition of the second, and since international timescales underpin modern-day technology such as telecommunications and navigation systems, the work will benefit end users across a wide range of sectors in the longer term.

2 Need

International timescales underpin technology we all depend on, such as modern telecommunications and navigation systems. As these systems continue to evolve, the demands on the stability and accuracy of the reference timescales increases.

At the time this project was proposed, optical atomic clocks had overtaken caesium primary frequency standards, both in terms of fractional frequency instability and estimated systematic uncertainty. A future redefinition of the second was anticipated, and ten optical transition frequencies had been accepted as secondary representations of the second. However, no optical clock had contributed either to the computation of TAI or to the UTC(*k*) timescales maintained by national timing laboratories.

For routine contributions to timescales, significant improvements were necessary to improve the robustness of the optical clocks, so that high uptimes could be achieved without round-the-clock monitoring and frequent user intervention to recover failures. Tools for on-the-fly correction of systematic frequency shifts and automated validation of data were also required to provide data with sufficiently low latency.

Extensive and repeated frequency comparisons between independently developed optical clocks were needed to assess their long-term reliability and reproducibility, and to provide crucial information for the international metrology community, informing their discussions regarding the best candidate for the redefinition. Traceability to the present definition of the SI second was also critical, requiring regular comparisons between optical clocks and caesium primary frequency standards.

These steps were essential prerequisites for the redefinition of the SI second, as clearly expressed by the Consultative Committee for Time and Frequency (CCTF) in Recommendation CCTF 1 (2017) and in their international roadmap for a redefinition of the second. Tackling these challenges required a collaborative approach, since the realisation of international timescales is a global endeavour.

3 Objectives

The overall objective of this project was to bring European optical clocks to the stage where they regularly contribute to TAI via reporting to the International Bureau of Weights and Measures (BIPM). Specifically, the objectives were:

1. To improve the robustness of optical clocks and automate their operation, including tools for on-the-fly evaluation of systematic frequency shifts. The target was to achieve unattended uptimes of 80 % – 90 % over a few weeks for both trapped ion and neutral atom lattice clocks.

2. To investigate the international consistency of optical clocks through a coordinated programme of frequency comparisons. This programme included remote comparisons using both optical fibre links and GPS-based satellite techniques, providing for wide participation as well as the lowest possible fractional comparison uncertainties (below 10^{-18}). Optical frequency ratio measurements enabled consistency checks to be performed where no direct link between clocks existed. Traceability to the present definition of the SI second was provided by absolute frequency measurements relative to caesium primary frequency standards.

3. To demonstrate, both by simulation and experimentally, methods for incorporating optical clocks into local realisations of Coordinated Universal Time (UTC), i.e. the UTC(*k*) timescales maintained by national timing

laboratories. Different algorithms were tested and compared, along with methods for automated validation of the optical clock data.

4. To incorporate optical clocks into international timescales as secondary representations of the second, via the submission of data to the BIPM.

5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the optical metrology community, in close co-operation with the CCTF and its associated working groups.

4 Results

The project outputs delivered against each objective are described in turn in subsections 4.1 – 4.4.

4.1 Objective 1: Robustness of optical clocks

To improve the robustness of optical clocks, new approaches were developed for automatic long-term control of laser systems and for automated adjustment of optical setups, addressing both trapped ion optical clocks and neutral atom optical lattice clocks. The focus was on the systems that had been observed to require most frequent user intervention, and a variety of approaches were tested by different partners within the consortium to compare their effectiveness (section 4.1.1). Software was also developed to schedule and perform key operational checks that previously required operator intervention (section 4.1.2) and for on-the-fly correction of systematic frequency shifts (section 4.1.3). These developments enabled several partners to demonstrate unattended operation of optical clocks with high uptime (section 4.1.4).

4.1.1 Improvements to robustness

The laser systems used in optical clocks, in particular the stabilisation of clock lasers to high-finesse optical resonators and the components that are employed to generate light used for laser cooling, were identified as major components to be improved.

Frequency stabilisation of the clock laser to a high-finesse optical resonator that provides the short-term frequency stability of the clock and enables coherent interrogation of the atomic reference is a pre-requisite for proper operation of the clock. Experience was shared within the consortium, after which CMI, LUH and UMK developed automatic relocking solutions for their specific setups. One example, in which relock functionality is provided by FPGA-based loop filters, is shown in Figure 1. The performance of this system was determined by forcing unlock events by blocking the light to the ULE stabilisation cavity, and the average relock delay found to be about 200 ms.

For the generation of laser light at higher frequency, sum frequency generation in optical resonators is typically employed. To achieve the high laser intensities required, enhancement cavities are used, and their stabilisation provides challenges that are very similar to those encountered in the stabilisation of lasers to high-finesse optical resonators. At INRIM, the frequency doubling of a 798 nm tapered amplifier laser diode in a bow-tie enhancement cavity containing a LBO non-linear crystal was identified as one of the main limitations to reliability of the IT-Yb1 optical lattice clock. A system based on a PID controller and an Arduino was therefore developed to relock the cavity autonomously if external perturbations cause unlocking of the cavity (Figure 2).

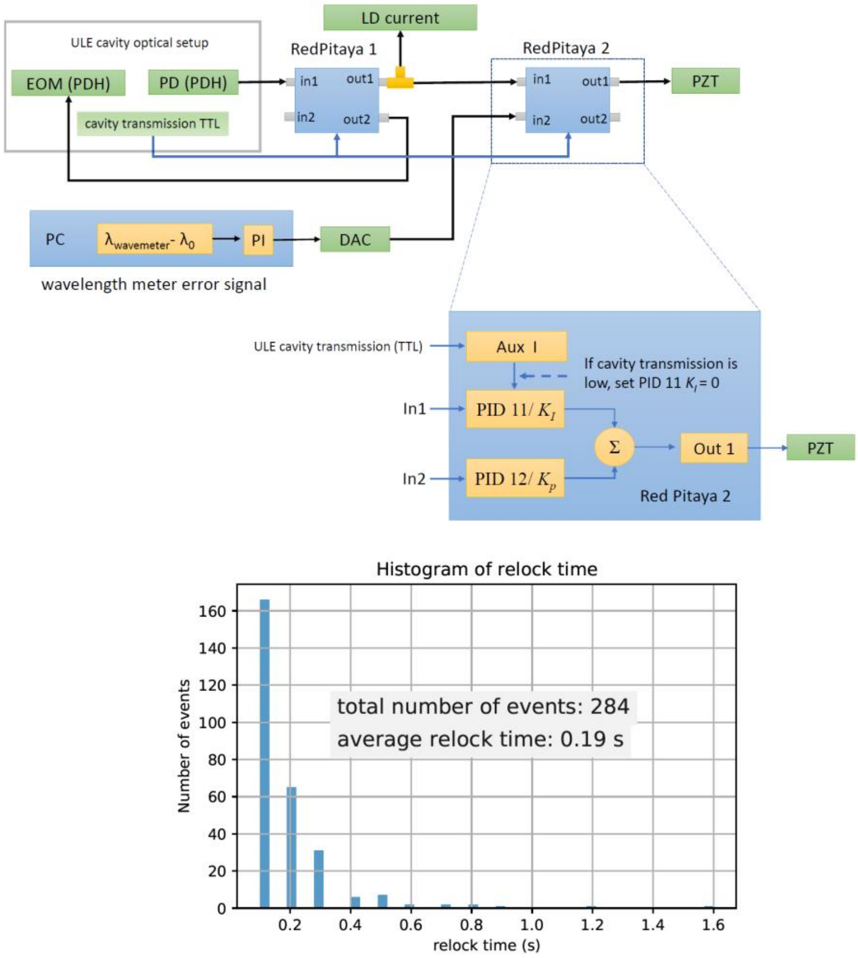

Figure 1. (Top) Automatic relocking system developed at LUH, used for the lasers addressing the $^1S_0$ – $^3P_0$ (clock) and $^1S_0$ – $^3P_1$ (detection and cooling) transitions in $^{115}In^+$, which are stabilized to high-finesse ULE cavities using the Pound-Drever-Hall technique. Both systems use FPGA-based locking electronics. (Bottom) Histogram of relock times after forced relock events.

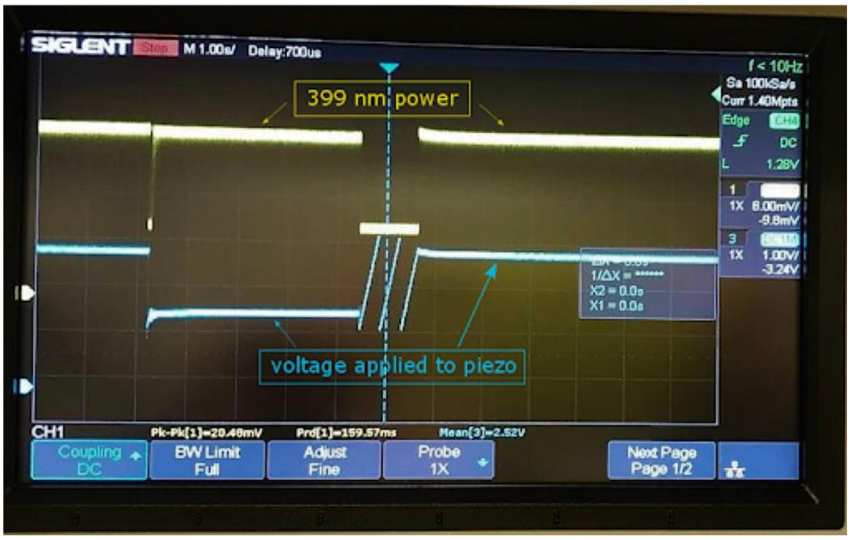

Figure 2. Illustration of the INRIM automated relocking system for the frequency doubling cavity in action, showing the control signal and the output power signal in the case where the proper operation was intentionally interrupted.

Enhancement of the power of available laser light is in some instances obtained from powerful slave laser diodes that are injection seeded by external master laser light. This requires a good overlap between the master and slave laser optical mode, as well as a proper adjustment of the temperature and current of the slave laser diode. Within the project, OBSPARIS/LNE, UMK, LUH and NPL all developed control units suitable for their setups that automatically correct the slave laser current to achieve robust long-term operation with blue and near-infrared laser radiation, sharing experience where appropriate.

To achieve optimal laser cooling conditions, cooling lasers need to be stabilised with a frequency stability much better than the linewidth of the cooling transition. A similar level of laser frequency stabilisation is required for the laser used to confine neutral atoms in lattice clocks. Techniques for meeting these requirements were also developed within the project. For example, at LUH software was developed that permits laser stabilisation using a commercial wavelength meter, and this tool for remote laser stabilisation and monitoring was published on the open source GitHub project. At PTB the combination of a wavemeter and a frequency comb was used to obtain even lower frequency instability for a lattice laser.

Most of the optical clock setups within the consortium use optical fibres to guide light between laser setups and the vacuum chamber containing the atomic reference. Thermal fluctuations can cause pointing instabilities and consequently change the coupling efficiency of the laser light to the optical fibre. Within the project systems were therefore also developed by LUH and BGU to automatically realign such setups and to reliably recover full coupling efficiency within a short time.

4.1.2 Automation of operation

A further part of the work concerned the development and testing of software to schedule and perform key operational checks that previously required operator intervention, for example the measurement of environmental parameters necessary to correct for systematic frequency shifts.

Methods for ion-based optical clocks were developed at NPL, PTB and VTT, with all institutes making use of the ARTIQ environment that is based on python. With this software, routines for key experimental sequences can be launched immediately, or scheduled ahead of time. Routines were developed for ion loading, minimisation of residual electric fields via measurement of ion micromotion, and minimisation of magnetic fields via measurement of the Zeeman components.

Taking as a starting point the ARTIQ experimental control for the NPL $^{171}Yb^{+}$ optical clock, a RMG researcher from ROA worked to develop a new framework for the experimental sequence for the NPL Sr lattice clock. This involved the development of scripts for amplitude and frequency ramping of rf signals, to apply voltage ramps for open-loop control, and for closed-loop stabilisation of laser intensity.

For optical lattice clocks based on neutral atoms, stabilisation of the lattice laser using a frequency comb (for example at PTB) was shown to simplify operation, since routines for automatic optimisation of the lattice laser wavelength are no longer necessary.

Routines to recover automatically from certain erroneous clock states have been developed by NPL, PTB, VTT and UMK, 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 malfunction of the clock system.

4.1.3 On-the-fly correction of systematic frequency shifts

Experimental control systems were also extended to perform on-the-fly evaluation and correction of systematic frequency shifts. For this purpose, several routines were developed that measure the magnitude of residual frequency shifting parameters and store the acquired data in a database for use by the shift calculation routines.

For ion-based optical clocks, spectroscopy routines are used to determine residual electric and magnetic fields by measuring the micromotion and thermal motion of the ion and the energy difference between Zeeman components of atomic states, respectively. Such routines have been developed by PTB, NPL, and VTT. The effect of thermal radiation perturbing the trapped ion is derived from measurements with temperature sensors at PTB, NPL, VTT and LUH. Because of the high intensities required to drive the electric quadrupole clock transition in $^{171}Yb^{+}$, accurate determination of the corresponding frequency shift is required. At NPL the clock laser power is monitored and stabilised using photodetectors, while at PTB the intensity the shift is measured in-situ via spectroscopic techniques.

To enable an accurate on-the-fly correction of systematic shifts in lattice clocks, magnetic fields are monitored spectroscopically. The leading frequency shift results from thermal radiation and requires accurate monitoring of the environmental temperature. At NPL, PTB and OBSPARIS, data from several temperature sensors is recorded during operation. The software developed at INRIM for real-time evaluation of the blackbody radiation shift has been published as open source on GitHub.

These developments enabled OBSPARIS, PTB and NPL each to demonstrate on-the-fly evaluation and correction of frequency shifts in at least one of their optical clocks, which was important for later parts of the project. For example, it enabled daily evaluation of the frequency ratio between clocks participating in international comparisons with low latency (section 4.2.1), and was key to the demonstration of prototype optically steered timescales (section 4.3.3).

4.1.4 Demonstration of unattended long-term operation

These techniques for automatic long-term control of laser systems, automated adjustment of optical setups and automation of key operational checks were used at NPL, OBSPARIS and PTB to demonstrate unattended operation of optical clocks with high uptime, exceeding 80 % over 2 weeks for at least one optical clock in each laboratory. In all cases, a few longer periods of downtime were responsible for most of the downtime. The reasons for these and possible further engineering improvements were compiled. One example result, for the NPL strontium optical lattice clock NPL-Sr1 is shown in Figure 3.

For the OBSPARIS strontium optical lattice clock, a similar distribution of downtimes was obtained – many short interruptions with a far smaller number of long downtimes which account between them for most of the downtime. Over a 16-day period, from MJD 59384 to 59400, the total uptime achieved was 88.9 %.

At PTB, an ytterbium ion optical clock was operated with 87 % uptime for a period of 34 days from MJD 59639 to MJD 59670. More than 50 % of the clock interruptions were related to short losses of ion fluorescence that recovered within a few seconds. As for the other clocks, the majority of the downtime resulted from a few much longer downtime events that required human intervention to recover.

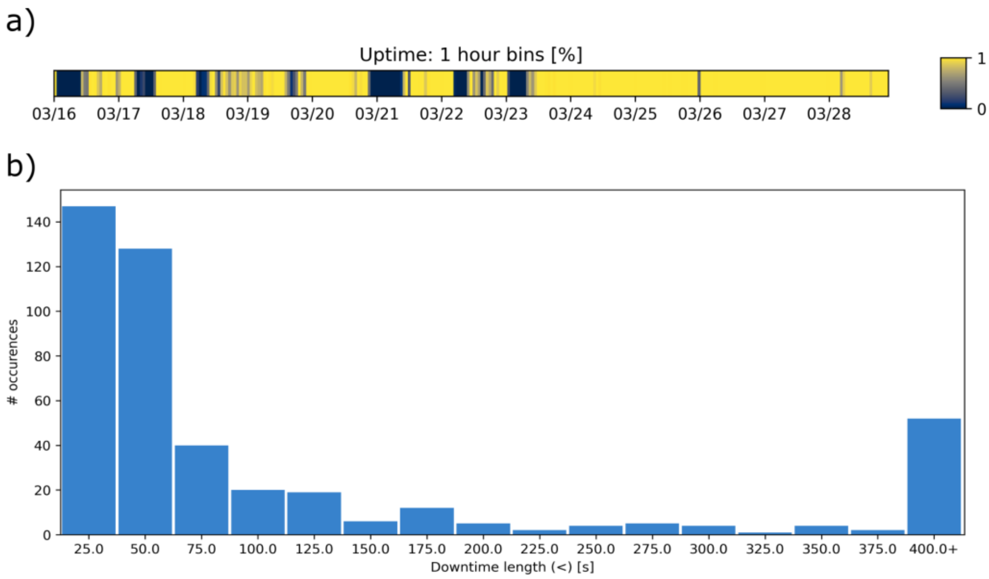

Figure 3. (a) Uptimes for the NPL strontium optical lattice clock (NPL-Sr1) during the two-week window 16th – 29th March 2022. The validity data has been binned per hour, with the colour map indicating the mean uptime for that hour. Over the whole period the uptime was 80 %. (b) Histogram of downtime length for the same period, with bins up to and including the value indicated. Thanks to the automated recovery systems implemented during the project, the median downtime length was 36 s.

4.1.5 Key results and conclusions

The objective of achieving unattended uptimes of 80 % – 90 % over a few weeks was achieved for at least one optical clock in each of three laboratories, and these clocks included both trapped ion and neutral atom lattice clocks. The improvements to robustness and automation that enabled this to be achieved included tools for on-the-fly evaluation of systematic frequency shifts. Prior to the start of the project, such high uptimes had only been achieved with round-the-clock monitoring and frequent user intervention, which is unsustainable over the long periods required for optical clocks to make routine contributions to timescales.

4.2 Objective 2: International consistency of optical clocks

The international consistency of optical clocks was checked through a coordinated programme of frequency comparisons between clocks developed independently in different countries. The participating clocks are listed in Table 1. Of these, the $^{88}Sr^{+}$ clock at VTT and the $^{115}In^{+}$ clock at LUH were completed and operated for the first time as part of the project, and the ^{88}Sr clock at UMK also joined international clock comparisons for the first time.

A RMG researcher from ROA contributed to an improved evaluation of some systematic frequency shifts in the OBSPARIS ^{87}Sr optical lattice clocks, specifically an assessment of the background collision shift and the residual lattice light shift. Measurements at OBSPARIS were performed in partnership with LNE, and measurements at UMK were performed in partnership with SRC PAS.

The programme of frequency comparisons included both local and remote optical clock comparisons, which are described in sections 4.2.1 and 4.2.2 respectively. The comparisons generated a dataset with significant correlations between the different measurements, which are discussed in section 4.2.3.

Clock	Institute
^{87}Sr	OBSPARIS, NPL, PTB
^{88}Sr	UMK
^{171}Yb	INRIM, NMIJ
^{199}Hg	OBSPARIS
$^{88}Sr^{+}$	VTT, PTB
$^{115}In^{+}$	LUH
$^{171}Yb^{+}$(E2)	NPL, PTB
$^{171}Yb^{+}$(E3)	NPL, PTB
^{87}Rb	OBSPARIS
^{133}Cs	INRIM, OBSPARIS, NPL, PTB

Table 1. Clocks participating in the coordinated programme of frequency comparisons. These included optical clocks based on eight different reference transitions, seven of which have been designated as secondary representations of the second by the CCTF. Also included were one microwave secondary representation of the second (^{87}Rb) and several caesium fountain primary frequency standards.

4.2.1 Remote clock comparisons

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

During the project, a new optical fibre link was therefore set up between Paris and Turin, to extend the reach of the European optical clock network and allow the ^{171}Yb optical clock at INRIM to join international comparisons by fibre link for the first time. A schematic of this link, which was set up, optimised and characterised as a collaborative activity between CNRS, OBSPARIS, LNE and INRIM, is shown in Figure 4. It has demonstrated robust performance with long-term fractional instability and accuracy below the 10^{-18} level, limited by the out-of-loop validation (Figure 5). This extension to the European infrastructure means that optical clocks in four different European laboratories (INRIM, NPL, OBSPARIS and PTB) can now be compared at a level commensurate with the performance of state-of-the-art optical clocks.

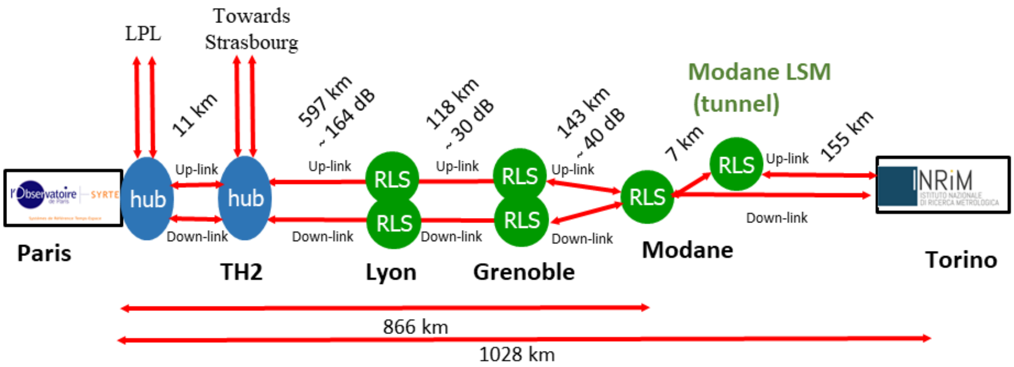

Figure 4. A schematic showing the new fibre link between OBSPARIS and INRIM.

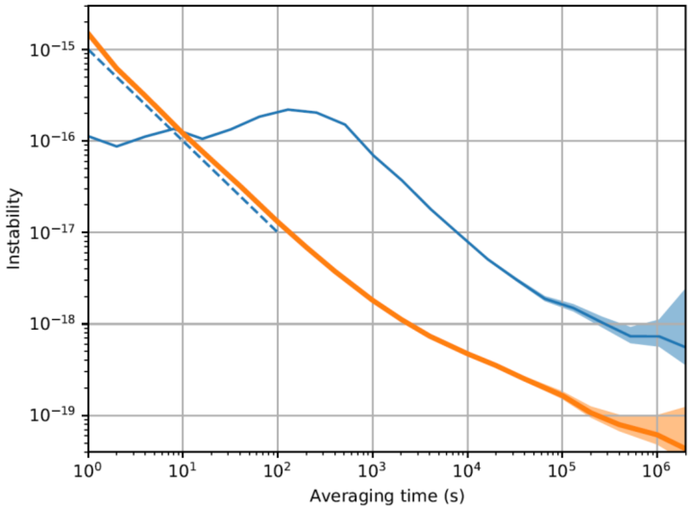

Figure 5. Measured and expected instability of the new fibre link between OBSPARIS and INRIM. The orange continuous line corresponds to the end-to-end link instability of the OBSPARIS-Modane-OBPARIS link. The blue solid line shows the measured instability of the INRIM-Modane segment, which is dominated by that of the link used for validation. The blue dashed line represents the expected instability of the Modane-INRIM link from delay-unsuppressed noise. [From C. Clivati et al., Phys. Rev. Applied 18, 054009 (2022).]

Two coordinated programmes of frequency comparisons were carried out during the project. To maximise the number of clocks that could be included, satellite-based comparison techniques were used in additional to optical fibre links. Not only did this allow laboratories not yet linked by fibre to join the measurement campaigns, it also enabled us to create a connection to frequency standards outside Europe, as satellite-based methods are the only techniques so far able to compare clocks operating in different continents. Specifically, the campaign included a ^{171}Yb optical lattice clock belonging to our collaborator NMIJ in Japan.

The first campaign was scheduled for March 2020 and was badly impacted by the initial wave of the COVID-19 pandemic. The second campaign, in March 2022, was far more successful. Eleven optical clocks in seven different countries were compared over a period of more than one month, making this the most extensive comparison of optical clocks performed to date (Figure 6). All laboratories operated GNSS-based satellite links, whilst three were also able to operate fibre links, enabling a comparison of two independent link technologies. In total, 27 remote frequencies were measured during the campaign.

The comparisons via fibre link reached 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. However the complete dataset does include a few internal inconsistencies, which may be resolved prior to publication.

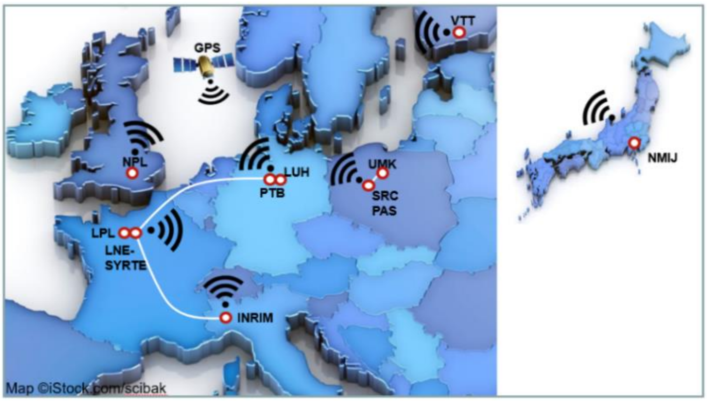

Figure 6. Scope of the March 2022 clock comparison campaign, which involved 11 optical clocks in 7 different countries, including one outside Europe.

4.2.2 **Local clock comparisons**

The remote comparisons were supplemented by local optical frequency comparisons. The comparisons carried out fell into two categories: local optical frequency ratio measurements and absolute frequency measurements relative to caesium primary frequency standards.

Local optical frequency ratio measurements can provide consistency checks without the need for a physical link between locations, if the same ratio is measured independently in different laboratories. This is particularly helpful in enabling European optical clocks to be compared with those in other continents, even though no high accuracy links are available over such long distances.

The inclusion of absolute frequency measurements in the comparison programme was critical to allow the frequencies of the optical clocks to be determined with the lowest possible uncertainty relative to the current definition of the second. This is essential to maximise the impact of including them in international timescales and to avoid any discernible discontinuity occurring at the point of an anticipated future redefinition of the second.

During the project, 51 local clock comparisons were performed between clocks on the same site. Of these, 33 were absolute frequency measurements and 18 were frequency ratios not involving Cs (mostly optical frequency ratios, but some involving the ^{87}Rb microwave secondary representation of the second). These local optical frequency comparisons included the measurement of several optical frequency ratios that had never been determined directly before. Most of the local frequency ratio measurements had uncertainties in the low parts in 10^{17} range, with one reaching a fractional uncertainty of 4.1×10^{-18}.

The 33 new absolute frequency measurements were made either by using a local caesium fountain primary frequency standard or by using International Atomic Time (TAI) to make the link to the SI second. In most cases the uncertainties in the absolute frequencies were dominated by the reference to the SI second.

4.2.3 **Correlation analysis**

The coordinated nature of the comparison programme led to a dataset in which there are significant correlations between individual frequency ratio measurement results.

Prior to this project, correlations had been essentially ignored by the joint Frequency Standards Working Group (WGFS) of the Consultative Committee for Time and Frequency (CCTF) and Consultative Committee for Length (CCL) in calculating optimised frequency values and uncertainties for secondary representations of the second, even though this can lead to biased frequency values and underestimated uncertainties. NPL and INRIM therefore collaborated to prepare guidelines on the evaluation and reporting of correlation coefficients between frequency ratio measurements, which are available on our project website. These guidelines discuss ways in which correlations between frequency ratio measurements may arise, and describe how they can be quantified. Worked examples are presented based on measurement data available in the published literature and include several examples of very significant correlations that were neglected in the 2017 update to the list of CIPM recommended frequency values. Suggestions are also presented as to how the information necessary to compute the correlation coefficients might be gathered from the groups performing such measurements, for future updates to the list. These guidelines were shared with the WGFS and strongly influenced the 2021 update to the list of recommended frequency values (section 4.4.1), ensuring that it was underpinned by a more robust analysis of the available data.

The guidelines were also used by other members of the consortium to compute the correlation coefficients between the various frequency ratios measured in this project. In total 313 non-zero correlation coefficients were evaluated between pairs of frequency ratio measurements, of which 135 had a magnitude ≥ 0.1 and 40 had a magnitude ≥ 0.5. A graphical representation of the correlation coefficients between the 20 different remote ratios measured via satellite links in the 2022 campaign is shown in Figure 7.

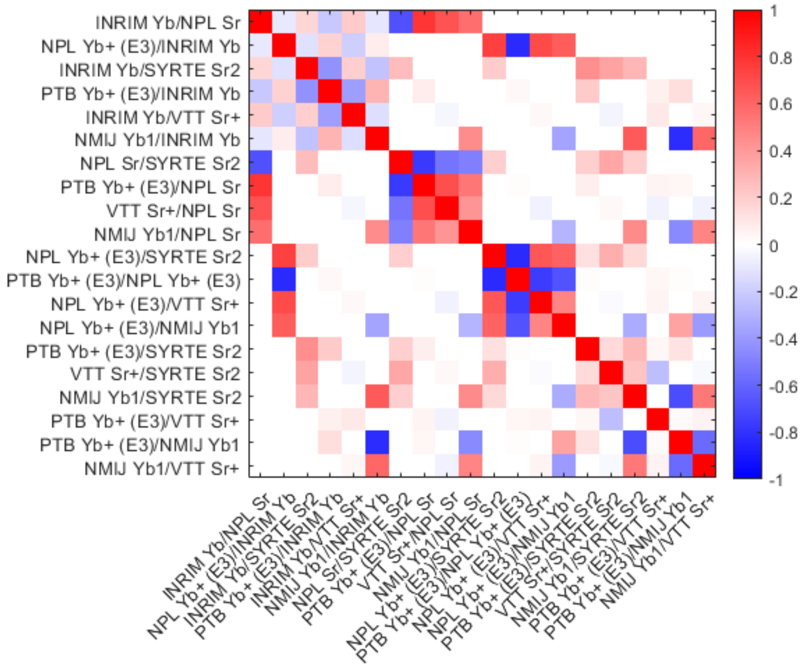

Figure 7. Visualisation of the correlation matrix for the clock frequency ratios measured via GNSS satellite links in March 2022.

4.2.4 Key results and conclusions

The objective of investigating the international consistency of optical clocks through a coordinated programme of frequency comparisons was therefore met, with the newly extended European optical fibre network having been shown to be capable of supporting comparisons with long-term fractional instability and accuracy below 10^{-18}. The comparison campaign carried out in March 2022 was the most extensive ever performed, involving eleven optical clocks in seven different countries. Measurements of local optical frequency ratios included several that had never before been determined directly, and comparison uncertainties for the most advanced optical clocks were reduced by an order of magnitude or more compared to the state-of-the-art at the start of the project.

4.3 Optical clocks in UTC(*k*) timescales

The target of this work, enabled by the advances in optical clock robustness and reliability (section 4.1), was to realise prototype UTC(*k*) timescales based on inputs from optical clocks, in an operating mode that does not rely heavily on the availability of hydrogen masers with the lowest possible instabilities.

The first part of the work focused on the real-time validation of the experimental data, including the development of robust methods for automated detection and removal of cycle slips and outliers (section 4.3.1). In parallel algorithms were developed for using such validated data to effectively apply steering corrections to the flywheel oscillator (hydrogen maser) generating the timescale (section 4.3.2). These were tested using simulated and historical optical clock data. Finally, several experimental prototype UTC(*k*) timescales were demonstrated, and their performance assessed (section 4.3.3).

4.3.1 **Automated validation of optical clock data**

For the real-time validation of the experimental data, it was necessary to consider the whole of the metrological chain connecting the optical clocks to the flywheel oscillators (hydrogen masers) generating the timescales. This required local frequency links and frequency combs to be considered as well as the optical clocks themselves.

Several approaches were developed to detect cycle slips or another anomalous behaviour in the links between the atomic reference and the flywheel, and their effectiveness compared by processing of real measurement data.

The light of the optical ultrastable oscillator that forms part of an optical clock is delivered to the atoms and to the frequency comb via phase-noise compensated optical fibre links. For each fibre, the AC output of a Michelson interferometer used to detect the propagation noise is phase locked to an accurate reference. Failures in this lock lead to cycle slips in the phase relation between the locked output and the reference, and it was demonstrated by NPL, OBSPARIS, LNE and INRIM that a direct in-loop counting of the locked output enables these to be detected as they appear as data points that are offset by an integer number of hertz (for frequency counters operated in Pi mode), clearly standing out from the shot-to-shot noise of the measurement, which is typically around 1 mHz (Figure 8). An out-of-loop scheme comparing two phase-locked fibres, one at rest, and the second purposely mechanically stressed, led to the same result, confirming the reliability of the approach. A more sophisticated approach developed at PTB, based on tracking the interferometer output using an FPGA, was also demonstrated to detect potentially erroneous frequency measurements, and may even allow the nature of the incident that led to a cycle slip to be identified.

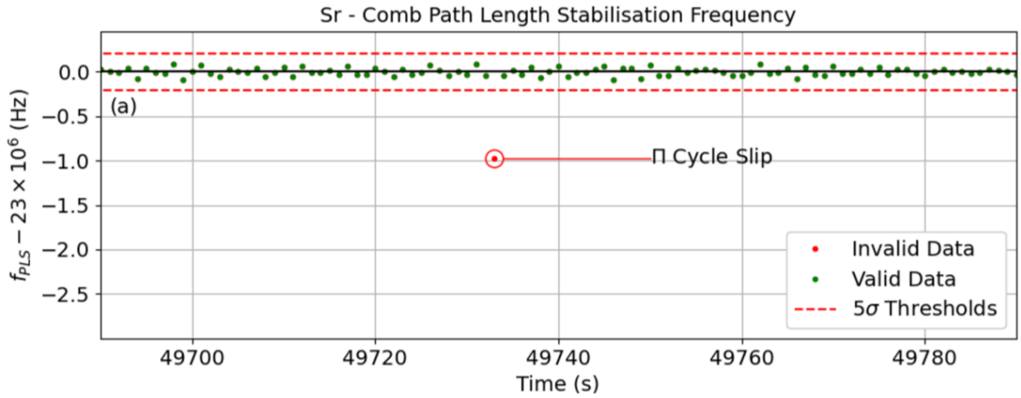

Figure 8. Example data showing the beat note used for path length stabilisation of the local link between NPL's Sr lattice clock and frequency comb laboratories. A cycle slip is easily identifiable as the point that is offset by 1 Hz and can be flagged using a 5σ filter.

Optical frequency combs are used to determine the frequency ratio between the optical local oscillator and the hydrogen maser flywheel. One method to detect inaccuracies arising from the frequency comb, demonstrated by OBSPARIS, LNE and INRIM, relies on the simultaneous measurement of the same ratio by two independent combs. In such a setup the noise of the oscillators is common mode and cancels out in the difference between the two measured ratios, with instabilities or inaccuracies due to the combs standing out of the noise in a similar way to cycle slips on short optical fibre links. An alternative method, demonstrated at NPL, uses only a single comb operated in a transfer-oscillator configuration and relies on the derivation of the frequency ratio by two complementary methods: one implemented in hardware, the other resulting from calculations performed in software. With sufficiently different implementation and filtering of the relevant signals in the two methods, it was shown that anomalous behaviour of the frequency comb results in a clear signature in the difference between the two extracted ratios.

For the optical clock itself, the monitoring of physical parameters and the operational environment were shown to enable objective criteria to be set to assess the validity of the data. For instance, the time history of Zeeman splitting measurements, or of successive frequency corrections of the clock laser locked to the atoms, feature particular statistical distributions in normal operation. Any new measurement outside this normal distribution indicates that the status of the clock must be considered as invalid for a certain time, which can be estimated based on the magnitude of the detected perturbation. Other approaches demonstrated for assessing the validity of the data included the monitoring of on-the-fly moving averages of the detected atom number or of the transition probability. Too low an atom number or too sudden a change of transition probability corresponds to an operation regime in which data must be considered invalid until the system recovers (Figure 9).

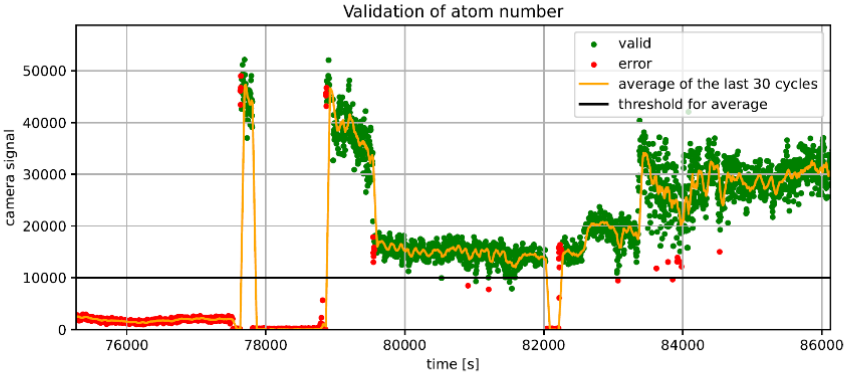

Figure 9. Moving average of the trapped atom number in the ^{88}Sr optical lattice clock at UMK, with the assessed validity of each data point indicated.

4.3.2 Steering algorithm development

While microwave clocks used to steer UTC(*k*) timescales usually feature an uptime close to 100 %, this is not always the case for optical clocks: although they have better stability and accuracy their availability is generally lower. The steering algorithms therefore need to handle this lower availability. They may also have to adapt to possible lags between data acquisition and correction, as well as to random changes in the frequency drift of the flywheel.

INRIM, POLITO and GUM designed algorithms able to adapt to these conditions and tested and optimised them using simulated and historical optical clock data. The simulated datasets were produced using noise models of hydrogen masers based on data shared by other members of the consortium.

An example of the results obtained using simulated data is shown in Figure 10. It was demonstrated that a continuously available clock enables the timescale fluctuations to be maintained below 1 ns over a period of 6 months. A situation in which data is accumulated only on one day a week, with gaps of several months, proved sufficient to keep the fluctuations below 6 ns over the same period.

Separately, it was shown that a lag of one day in data availability still enables timescale fluctuations at the 1 ns level to be achieved, but that higher latency can rapidly lead to excursions of several tens of nanoseconds, with fluctuations in flywheel drift at the 10^{-16} level.

Tests of the steering algorithms using historical data from comparisons between hydrogen masers and optical clocks produced similar results to those obtained using simulated data: it was shown that fluctuations could be maintained below 1 ns with an optical clock uptime of 65 %, compared to within 6 ns over 6 months with an optical clock uptime of 11 % (Figure 11). This study confirmed the capacity of the algorithms to adapt to realistic operational conditions.

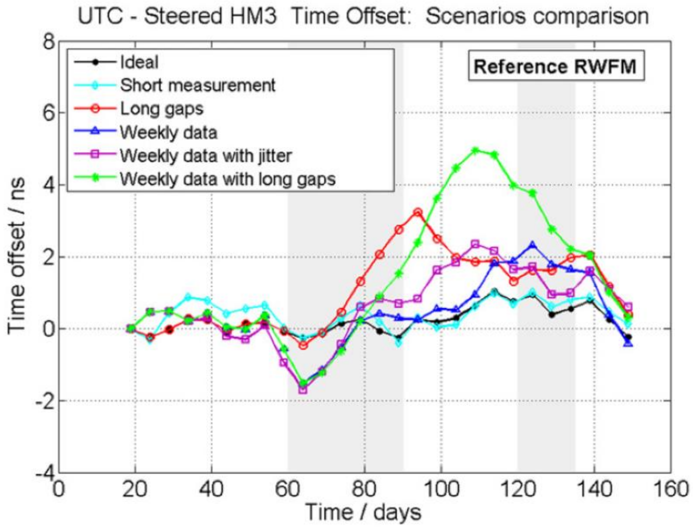

Figure 10: Timescales obtained from synthetic data generated based on the noise models of operational H-masers within the consortium. The steering was applied by the algorithms developed within the project.

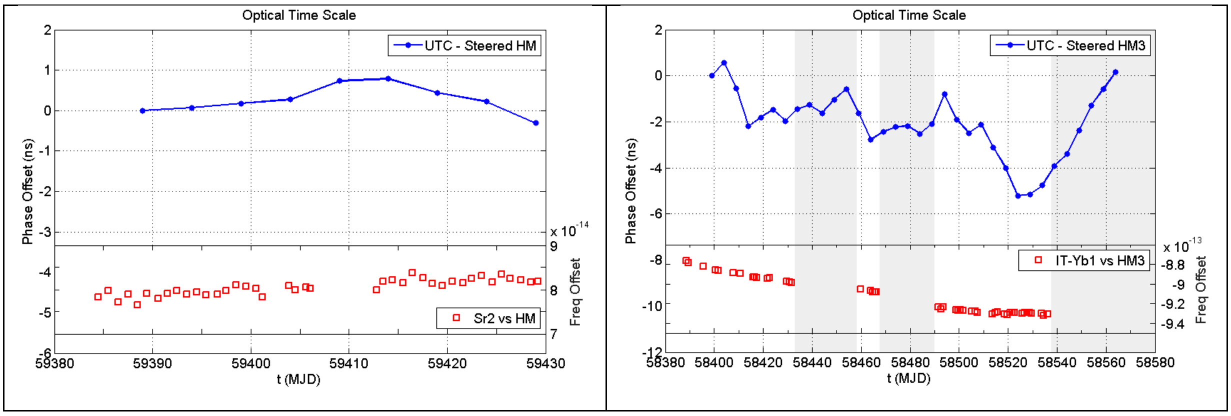

Figure 11: Timescale steering tests performed using historical data. The performance is as expected from the results obtained with simulated data: fluctuations are smaller than 1 ns during one month in the case of high uptime (left), while they remain below 6 ns over 6 months in the case of low uptime/long gaps (right).

4.3.3 Prototype UTC(*k*) steering using optical clocks

The automated real-time validation procedures and the lessons learned from the algorithm testing were exploited to realise experimental prototypes of optically steered timescales, referred to as UTCx(*k*). In parallel with the March 2022 international clock comparison campaign, NPL, OBSPARIS/LNE and SRC(PAS) established prototypes steered by data from one or more optical clocks.

At SRC PAS, the maser flywheel was steered using data from an optical clock in a different location, at UMK, although technical issues with one part of the measurement chain impacted the stability of the resulting timescale UTCx(AOS). Nevertheless this work demonstrated that it is possible for laboratories operating timescales to collect and use data from optical clocks located in other institutes.

At NPL and OBSPARIS high uptimes of the optical clocks and the measurement chain connecting these to the local hydrogen maser flywheels were achieved, with the result that the prototype optically steered timescales UTCx(NPL) and UTCx(OP) remained less than 2 ns away from UTC over 30 days, despite a few data validation issues and technical issues associated with the frequency offset generators used for steering. These two UTCx(*k*) timescales were also compared directly (Figure 12), the first time such a measurement had been carried out. The offset between the two prototype timescales was demonstrated to remain smaller than the offset between the corresponding operational UTC(*k*) timescales over the same period.

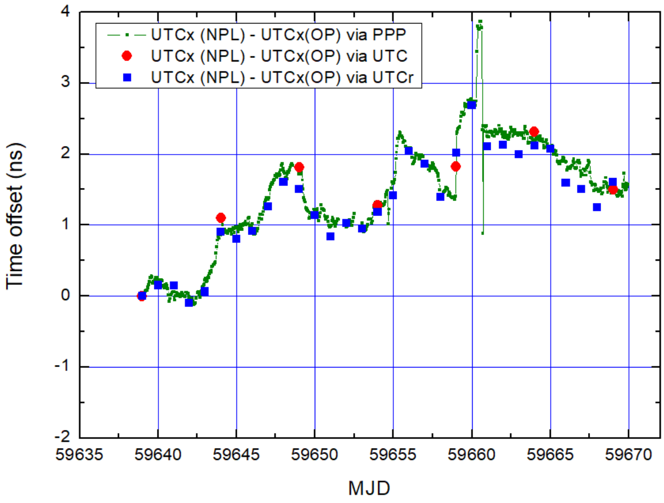

Figure 12. Direct comparison between the prototype optically steered timescales UTCx(NPL) and UTCx(OP), via GPS PPP links, UTC and UTCr. The two timescales remained less than 4 ns apart over 1 month, despite some technical issues.

4.3.4 **Key results and conclusions**

The objective of demonstrating, both by simulation and experimentally, methods for incorporating optical clocks into the UTC(*k*) timescales maintained by national timing laboratories was thus successfully achieved. A first direct comparison was carried out between two prototype optically steered timescales, each of which used data from two optical clocks operating with high uptimes. The offset between these two prototype timescales remained smaller than the offset between the corresponding operational UTC(*k*) timescales over the duration of the test.

4.4 Optical clock contributions to TAI

Incorporation of optical clocks into international timescales as secondary representations of the second is achieved through comparison of the optical clocks with clocks (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.

With the current definition of the SI second based on the caesium hyperfine transition, optical clocks may only contribute to TAI with the uncertainty of the recommended value for the secondary representation of the second. The work contributing to this objective therefore fell into two parts: the derivation of optimised frequency values for secondary representations of the second (section 4.4.1) and the collection and submission of optical clock data for use by the BIPM in computing TAI (section 4.4.2).

4.4.1 **Optimised frequency values for secondary representations of the second**

The recommended frequency values for secondary representations of the second are determined based on the worldwide body of clock comparison data, using least-squares analysis procedures developed during the earlier EMRP SIB55 ITOC project.

In this project, two evaluations of the expanding body of clock comparison data available worldwide were performed, first in conjunction with the work of the CCL-CCTF WGFS in 2020, completed in March 2021, and then at the end of the project, completed in October 2022. To verify the results obtained from the NPL software developed during the ITOC project, two independent software codes were written by INRIM and OBSPARIS. Each piece of software can calculate optimised values for each frequency ratio and absolute frequency value in the least-squares adjustment and check the self-consistency of the input data.

The first evaluation was based on all available optical frequency ratio and absolute frequency measurement results from both the consortium and the wider community. Various iterations of the analysis were performed to feed directly into the work of the CCL-CCTF WGFS, with the final analysis being performed on the official input data set agreed by that group. The analysis considered 105 input data points (Figure 13a), of which 37 were new measurements reported since the previous update to the CIPM list of recommended frequency values in 2017. A key difference from the previous adjustments is that detailed consideration was given to correlations between the individual frequency measurements to ensure that the frequency values derived are unbiased and that their uncertainties are not underestimated. This change in the WGFS practice was strongly influenced by work in this project, in particular our guidelines on reporting on evaluation and reporting of correlations coefficients (section 4.2.3). In total, 483 correlation coefficients were calculated and included in the analysis. These coefficients included the correlations from the systematic uncertainties of caesium fountain primary frequency standards (due to multiple measurements with the same fountains) and between different measurements performed within the same coordinated measurement campaigns. The results obtained from the independently written software (Figure 14) were demonstrated to agree to at least the part in 10^{19} level, significantly below the uncertainties of the recommended frequency values.

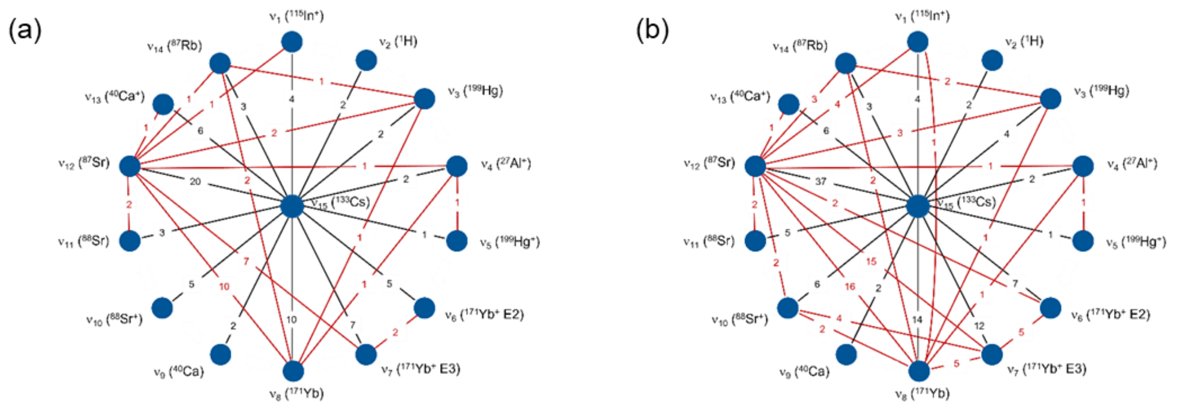

Figure 13. Input data used in (a) the first least-squares adjustment completed in March 2021, and (b) the second adjustment completed in October 2022, including unpublished frequency measurements collected during the project. Black lines represent absolute frequency measurements, while red lines represent frequency ratio measurements not involving caesium. The numbers indicate the number of measurements made of each absolute frequency or frequency ratio.

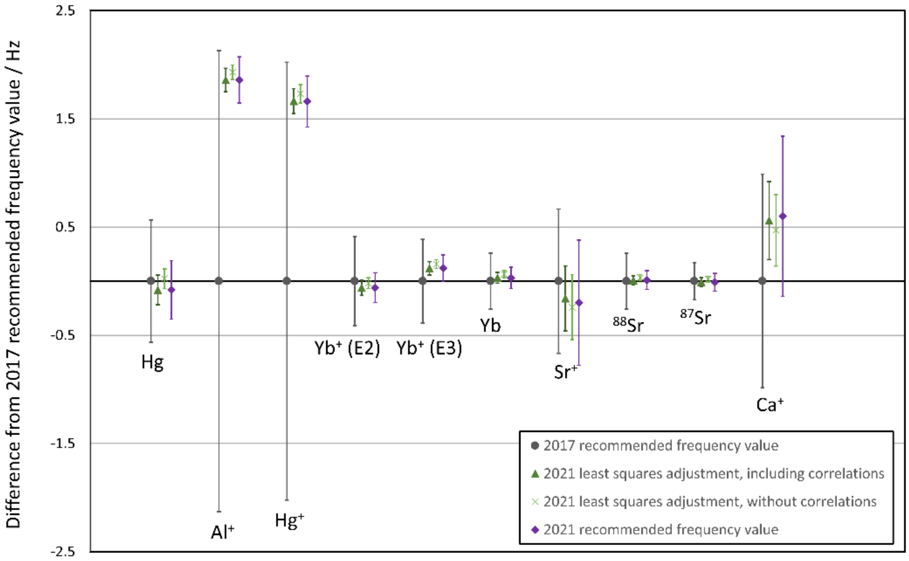

Figure 14. 2021 adjusted frequency values and uncertainties for ten optical frequency standards, showing that neglecting correlations can bias the frequency values obtained from the fit. Also shown are both the 2017 and 2021 recommended frequency values and uncertainties. All ten optical frequency standards are now secondary representations of the second.

The second least-squares adjustment, performed at the end of the project, included new data available from local and remote frequency comparisons carried out during the project, in particular the March 2022 remote clock comparison campaign (section 4.2.1). Altogether, 73 new measurements and 313 new non-zero correlation coefficients were added to the input data, resulting in a total of 178 frequency measurements and 796 correlation coefficients (Figure 13b). The results obtained from the independently written software again agreed to at least the part in 10^{19} level, significantly below the uncertainties of the recommended frequency values, giving additional verification of the accuracy of the calculations.

Including these new input values results in improved uncertainties and in significant changes to the values of the adjusted frequencies for $^{88}Sr^+$ and $^{115}In^+$ (Figure 15). $^{115}In^+$ is not yet a secondary representation of the second as the $^{115}In^+$ measurements considered by the CCL-CCTF WGFS in 2020 – 2021 had uncertainties at the level of 1 part in 10^{15} or higher. New measurements collected during the project with the $^{115}In^+$ clock at LUH, including optical ratios with uncertainties at the part in 10^{17} level mean that $^{115}In^+$ could be a candidate for a new secondary representation the next time the list of recommended frequency values is updated by the WGFS. A significant change of more than one standard deviation was observed in the adjusted frequency of $^{88}Sr^+$, which is already a secondary representation of the second, even though the WGFS try to take a conservative approach to uncertainty estimation. New measurements collected during the project at PTB and VTT are in good agreement, indicating that an update to the recommended frequency value for the optical clock transition in $^{88}Sr^+$ is likely to be necessary.

The second evaluation included a significant body of unpublished data, which shows some internal inconsistencies. Although these may be resolved prior to publication, this observation suggests that the cautious approach adopted by the WGFS when considering the scarcity of input data may need to be extended to the case where optimised optical frequency ratios, rather than only absolute frequency measurements relative to caesium primary standards, are determined primarily by a single measurement. A further observation is that the new data collected within the project is quite fragmented, for example containing multiple absolute frequency measurements involving the same optical clock and caesium fountain. This has advantages in enabling the consistency of the measurements over time to be assessed, but it complicates the treatment of correlation coefficients for the least-squares adjustment as it significantly increases the number that must be computed. This highlights that it may be beneficial for the groups involved to consolidate the input data.

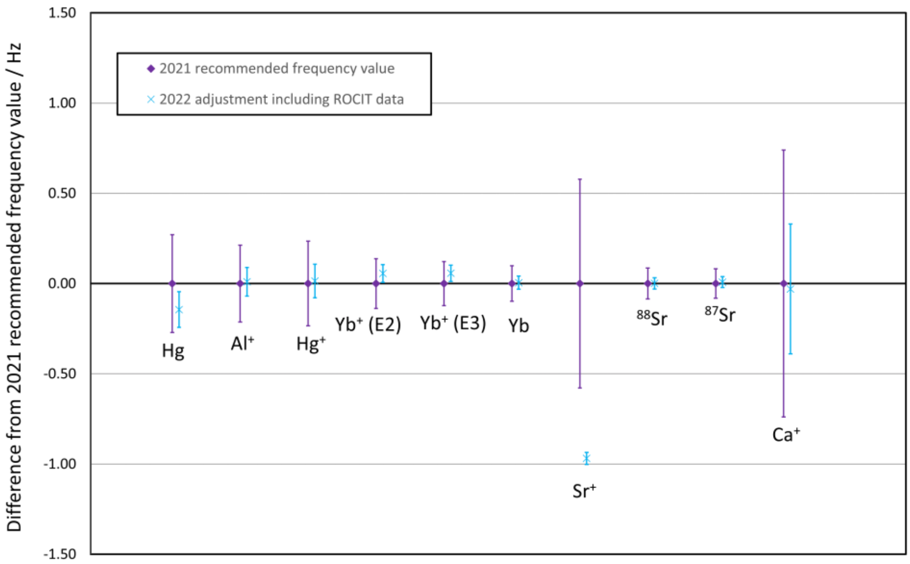

Figure 15. Adjusted frequency values and uncertainties of the ten optical secondary representations of the second, obtained from the least-squares adjustment performed in October 2022, which incorporated all new data obtained during the project. Results are presented as differences from the 2021 recommended frequency values.

4.4.2 Incorporation of optical clocks into International Atomic Time

To incorporate optical clocks into TAI, the BIPM require data from frequency comparisons between optical clocks and hydrogen masers used in the computation of TAI.

A pre-requisite for inclusion of a particular secondary representation of the second is approval by the CCTF Working Group on Primary and Secondary Frequency Standards (WGPSFS). Guidelines on how to collect, prepare and submit optical clock data to the BIPM were written by LNE and OBSPARIS, based on their previous experience with their Rb fountain and their Sr optical lattice clocks, and shared with the consortium. These guidelines outline the procedure for submission of primary and secondary frequency standard data, including the case of submission of data from new standards that have not contributed before. They advise groups working on optical clocks on how to prepare data for submission, in cases where they lack previous experience with secondary standards. The guidelines cover criteria that must be met for the first submission of a new standard, specifically the evaluation by the CCTF WGPSFS and a peer-reviewed paper describing the uncertainty budget. They also outline the data that must be provided in each submission, namely the period of evaluation, the frequency of a maser included in the computation of TAI as evaluated against the standard, the evaluated uncertainty of the standard during the measurement period and (for a secondary representation of the second), the relevant recommended frequency value.

During the project, twelve optical clocks within the consortium (at INRIM, NPL, PTB, OBSPARIS, UMK and VTT) measured a hydrogen maser used in the computation of TAI with measurement periods aligned with the 5-day reporting periods of Circular T. (In the case of UMK, the hydrogen maser was located remotely, at SRC PAS.) The clocks involved included both optical lattice clocks and ion clocks covering six secondary representations of the second ($^{171}Yb^{+}$ E2, $^{171}Yb^{+}$ E3, ^{171}Yb, $^{88}Sr^{+}$, ^{88}Sr and ^{87}Sr). 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. The optical clocks IT-Yb1, NPL-Sr1, PTB-Sr3, PTB-Yb1E2, PTBYb1E3 and SYRTE-Sr2 were all able to collect data with uptime greater than 70 % in some periods. For the data collected for the project, SYRTE-Sr2 demonstrated an uptime of 90 % in one 10-day period and NPL-Sr1 an uptime of 98 % in one 5-day period, while PTB-Yb1-E3 demonstrated an uptime of 85 % over a 35-day period.

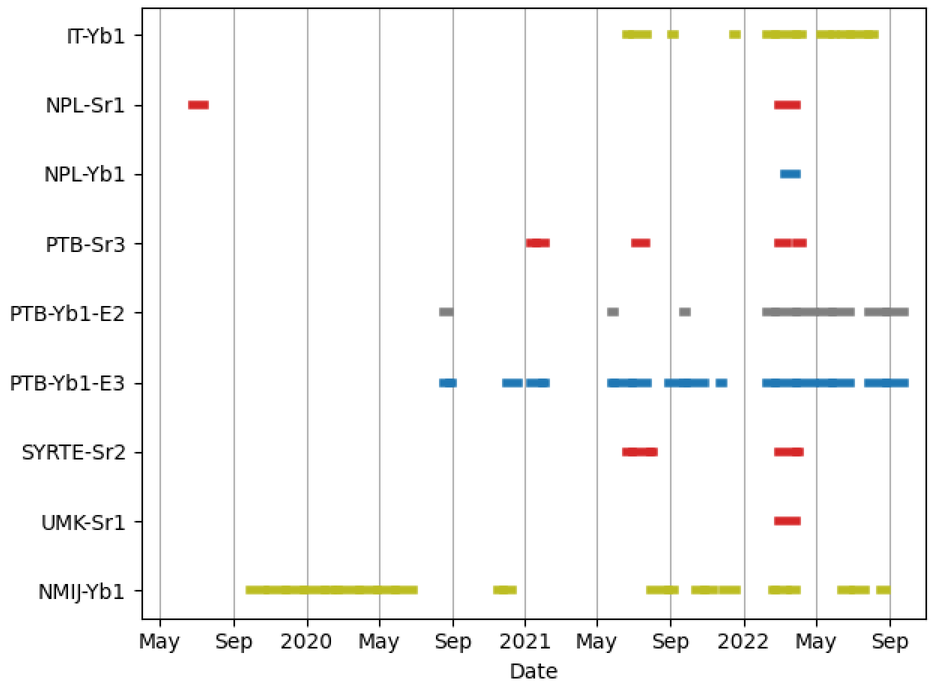

Figure 16. Graphical representation of the measurement of hydrogen masers using some of the optical clocks from the consortium, and collaborator NMIJ, during the project. (Some additional data, not included in this figure, was also collected, but later invalidated due to technical issues.) Note the many optical clocks collecting data at the same time in March 2022.

In November 2019, the INRIM Yb optical lattice clock IT-Yb1 received approval from the WGPSFS. The submitted data, which was collected prior to the start of the project, appeared in Circular T no. 383 (November 2019) and was used for TAI steering. The Sr optical lattice clocks at OBSPARIS had already been approved by the WGPSFS before the start of the project, and were included in Circular T on one occasion although not used for steering because it was recognised at that time that there was a need to update the recommended frequency of Sr.

NPL submitted data from their Sr optical lattice clock NPL-Sr1 to the BIPM shortly after the end of the project, and this standard is pending approval by the WGPSFS. Four other clocks have been operated and collected large amounts of data that can be used in their first submissions to the BIPM. A few difficulties delayed some submissions, such as the need for a well characterised systematic uncertainty following improvements to setups, the need for a peer-reviewed manuscript describing the uncertainty evaluation, and technical problems that invalidated some of the data collected. Nevertheless, the project has been instrumental in increasing the readiness of European optical clocks to receive approval from the WGPSFS and the collected data will be submitted pending updated uncertainty budgets and peer-reviewed publications.

Since their initial submissions, 14 further submissions of optical clock data have been made to the BIPM, five from one of the Sr lattice clocks at OBSPARIS and nine from the INRIM Yb lattice clock. All data was submitted with low latency (before the 4th day of the following month) and was used for TAI steering. This exceeded the target to make at least ten submissions to the BIPM, although these submissions came from fewer laboratories and clocks than originally anticipated.

Worldwide, there are now seven optical clocks that have contributed to TAI (Figure 17). Three of these (IT-Yb1, SYRTE-Sr2 and SYRTE-SrB) are from the consortium, one (NMIJ-Yb1) from our collaborator and three (NICT-Sr1, NIST-Yb1 and KRISS-Yb1) from the wider community.

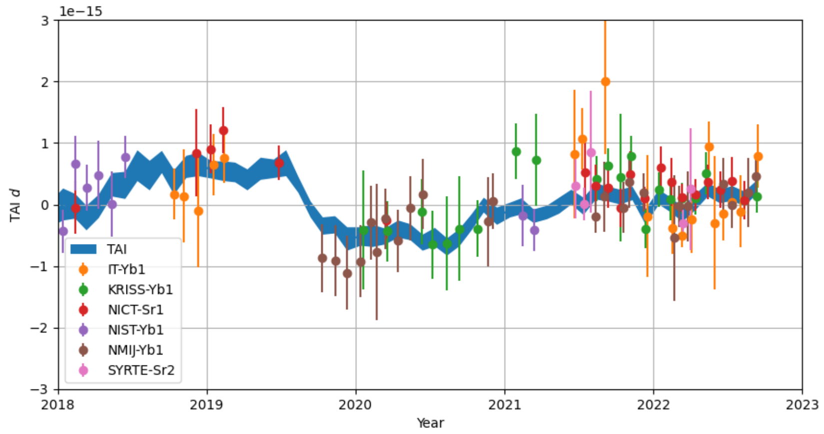

Figure 17. Optical clock measurements appearing in Circular T (points) compared with the duration of the TAI scale interval *d* (blue area). Data from https://www.bipm.org/en/time-ftp/other-products.

INRIM, NPL, OBSPARIS, PTB, UMK and VTT (together with collaborator NMIJ) operated their optical clocks at the same time in March 2022, corresponding to the coordinated measurement campaign organised within the project (section 4.2.1). The campaign resulted in 10 secondary representations of the second from 7 laboratories measured at the same time, for at least 20 days and with high uptime. With the submission of data from three of these optical clocks to the BIPM, the corresponding Circular T (no. 411) saw a record contribution of 5 optical clocks.

4.4.3 **Key results and conclusions**

The objective of incorporating optical clocks into international timescales as secondary representations of the second, via the submission of data to the BIPM, was achieved, with the target number of submissions being met. Although these submissions came from fewer laboratories and clocks than originally anticipated, other clocks collected large amounts of data with high uptime, which they will be able to use in their first submissions to the BIPM once peer-reviewed publications describing updated uncertainty budgets are available.

The new recommended values for standard frequencies approved by the CCTF in 2021, which were strongly influenced by work in this project, were used for the first time for the calculation of TAI in Circular T no. 412

(April 2022). This allowed optical clocks to steer TAI with lower uncertainty, as the recommended frequency values for six secondary representations of the second now have uncertainties at the limit set by caesium fountain primary frequency standards. The update therefore resulted in a significant increase in the weight of optical clocks in TAI (Figure 18).

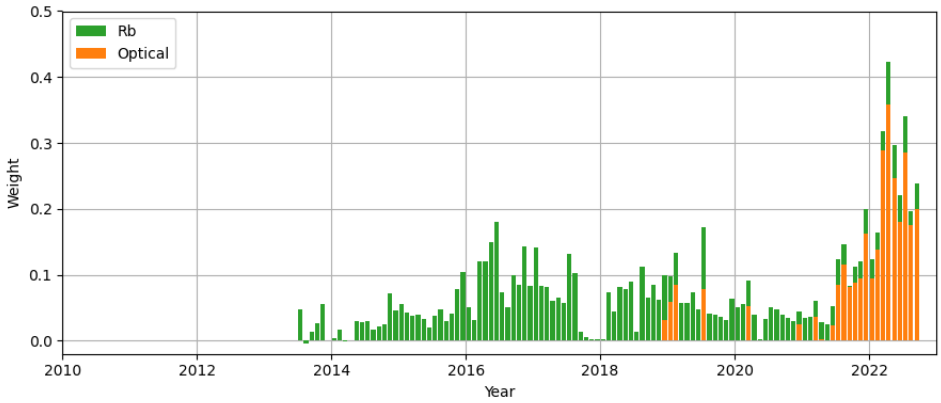

Figure 18. Graphical representation of the weights of secondary representations of the second in TAI, separated into the contributions from Rb and optical clocks. Data from https://www.bipm.org/en/time-ftp/other-products ("Fractional frequency of EAL from primary and secondary frequency standards").

5 Impact

The potential uptake of the project results by end users has been promoted by a range of dissemination activities such as presentations at conferences and workshops, and input to metrology committees. The project website presents an overview of the project, together with new updates and announcements, and also provides access to papers, reports and open data produced during the project. Fifteen peer-reviewed papers and two master's theses have been published. A list of stakeholders has been drawn up and formal collaboration agreements have been put in place with AIST/NMIJ and with the EMPIR 18SIB06 TiFOON consortium. One new optical clock from within the consortium has undergone evaluation by the WGPSFS, and there was extensive interaction with the CCTF and its working groups in the period leading up to the CCTF meeting held in October 2020. Training activities have included two talks at the "Autumn School on Clocks, Cavities and Fundamental Physics" and an invited tutorial lecture at PTTI 2020, as well as several seminars. A final two-day international workshop, held online to disseminate and discuss the results and findings from the project, was attended by more than 200 participants from around the globe.

Impact on industrial and other user communities

The hardware and software developed to improve the robustness and automation of laboratory optical clocks will benefit research groups and industrial organisations developing compact and portable optical clocks for field applications. Several project partners have strong links with European and national programmes that aim to develop such clocks for applications including geodetic height measurements, synchronisation of telecommunications networks and future satellite navigation systems. Trialling approaches on state-of-the-art laboratory clocks will speed up these efforts to commercialise optical clock technology, and some of the software developed has been made available to interested parties on GitHub following an open-source approach. Applications of clock subsystems also extend to other areas such as precision spectroscopy and quantum information processing. Automatic laser re-locking software is being used by at least one university outside the consortium, and knowledge gained within the project has been used to advise industrial organisations participating in ESA's Technology Research Programme.

Impact on the metrology and scientific communities

The most direct impact of this project is on the future realisation and dissemination of the SI unit of time.

Key outputs from the project are improved frequency values for secondary representations of the second and detailed information about the consistency of optical clocks within Europe. In this way the work has helped to build confidence that the new generation of optical clocks perform at the level expected according to the uncertainty evaluations for individual clocks. It will also help the international community to identify the most promising candidates for a future redefinition of the second.

The measurements and analysis have made significant contributions to improved recommended frequency values for secondary representations of the second, which are now at the limit set by the uncertainties of caesium fountain primary standards. The improvements in the robustness and automation of optical clocks will enable them to be operated regularly as secondary representations of the second, being used to steer local UTC(*k*) timescales and broadening the base of high accuracy clocks available for TAI steering.

These advances are giving European time and frequency metrology institutes a highly influential role within international discussions regarding the future of TAI and the anticipated redefinition of the second.

The work performed will also have spin-off benefits to fundamental physics. For example, comparisons between optical clocks with verified uncertainties can be used to set limits on possible present-day variation in fundamental physical constants, to test the predictions of special and general relativity and to set experimental constraints on dark matter detection. Some of the measurements performed in the project have already been exploited in this way.

Impact on relevant standards

Since the project addressed a future change in the definition and realisation of the SI unit of time, the route to impact was through the CCTF and its working groups. The consortium is well represented on these bodies, where information on the project progress and outputs was disseminated through tailored presentations and written reports.

Contributions to the Frequency Standards Working Group (WGFS) include improved measurements of optical frequency ratios and absolute frequencies involving seven out of the ten optical clocks currently designated as secondary representations of the second. Several measurements performed in the early stages of the project were submitted to the WGFS in 2020 for use in updating the list of recommended frequency values they maintain. This update, approved by the CCTF in March 2021, was strongly influenced by work carried within the project, in particular our guidelines on the evaluation of correlation coefficients between frequency ratio measurements. As a result of the 2021 update to the list, six secondary representations of the second now have fractional uncertainties below 2×10^{-16}, meaning that they can contribute to TAI with a similar weight to Cs primary frequency standards, if they achieve similar uptimes. Measurements performed later in the project will be submitted to the WGFS ahead of their next update to the list, expected in 2024.

Submission of optical clock data and detailed uncertainty budgets for assessment by the Working Group on Primary and Secondary Frequency Standards (WGPSFS) is expected to lead to approval for inclusion in Circular T, and (at the discretion of the BIPM) subsequent use for TAI steering. The result will be international timescales with improved stability. Two optical clocks from the consortium are now being used for TAI steering, one is pending approval by the WGPSFS as of December 2022, and others have gathered data that will be used for initial submissions.

Reports on the project outputs have also been presented to other working groups of the CCTF. In particular, the results and capabilities demonstrated within the project have influenced the international roadmap towards a redefinition of the SI second, prepared by a new task force set up by the Working Group on Strategic Planning (WGSP).

Longer-term economic, social and environmental impacts

Through its contributions to improving European and global time and frequency infrastructure, this project will bring economic benefits to end users across a wide range of sectors.

Users who are expected to benefit from higher stability reference timescales include the European Space Agency (ESA) and the European VLBI Network (EVN), both of whom operate large-scale facilities that rely on accurate time and frequency signals. Precise time and frequency standards and measurement also lie at the core of many technologies upon which society increasingly relies, the most notable being global navigation satellite systems (GNSS). European companies accounted for 25 % of the global GNSS market in 2015 and timescales with improved stability will further fuel this market by stimulating new applications of GNSS.

Networks of optical atomic clocks will have significant impact in the field of geodesy, as they can be used to measure the Earth's gravity potential with high temporal and spatial resolution via the gravitational redshift of their operating frequencies. In this way it will be possible to bring national height systems into alignment across Europe, as well as to check global and regional geoid models established by other methods. A unified height reference system incorporating measurements made with optical clocks could help prevent costly mistakes in engineering projects. It could also have significant impact on geodynamic and climate research, for example by allowing scientists to track seasonal and long-term trends in ice sheet masses and overall ocean mass changes. Such data provides critical input into models used to study and forecast the effects of climate change.

Accurate time and frequency references underpin numerous technologies that are almost taken for granted in everyday life. Apart from GNSS, systems such as electric power grids, mobile telecommunication networks and the internet all depend on time and frequency standards. The developments realised within this project will enable time and frequency to be disseminated with unprecedented stability and accuracy, not only to end users of the timescales maintained by European laboratories, but also globally through their impact on the international timescales TAI and UTC. As a result, it is expected to have widespread longer-term impact on innovation, science and daily life.

6 List of publications

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5. R. Lange, N. Huntemann, C. Sanner, H. Shao, B. Lipphardt, C. Tamm and E. Peik "Coherent suppression of tensor frequency shifts through magnetic field rotation" Physical Review Letters 125, 143201 (2020)

6. J. Lodewyck, R. Le Targat, P.-E. Pottie, E. Benkler, S. Koke and J. Kronjäger. "Universal formalism for data sharing and processing in clock comparison networks". Physical Review Research 2, 043269 (2020)

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10. C. Lisdat, S. Dörscher, I. Nosske and U. Sterr. "Blackbody radiation shift in strontium lattice clocks revisited". Phys. Rev. Research 3, L042036 (2021)

11. S. Condio. "Optical lattice clock with an amplified laser diode". Master thesis in physics at University of Torino (2021)

12. L. Seppäläinen. "Reducing the statistical and systematic uncertainty of the VTT MIKES $^{88}Sr^{+}$ ion clock". Master thesis in Engineering Physics from Aalto University (2021)

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