Publishable Summary for 18SIB05 ROCIT
Robust Optical Clocks for International Timescales

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 will tackle key steps that must be taken prior to the redefinition. The robustness of optical clocks will be improved so that they can run unattended for long periods, methods will be developed for automatic data validation, and the long-term reliability and reproducibility of the clocks will be assessed through a coordinated programme of international comparisons. By the end of the project several European optical clocks will be contributing on a regular basis to International Atomic Time as secondary representations of the second, improving its stability and accuracy. Since international timescales underpin modern-day technology such as telecommunications and navigation systems, this work will benefit end users across a wide range of sectors in the longer term.

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.

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

For routine contributions to timescales, the robustness of the optical clocks must be improved significantly, so that high uptimes can 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 are also required to provide data with sufficiently low latency.

Extensive and repeated frequency comparisons between independently developed optical clocks are needed to assess their long-term reliability and reproducibility. This will 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 is also critical, requiring regular comparisons between optical clocks and caesium primary frequency standards.

These steps are 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 requires a collaborative approach, since the realisation of international timescales is a global endeavour.

Objectives

The overall objective of this project is 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 are:

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 is 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 will include 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 will enable consistency checks to be performed where no direct link between clocks exists. Traceability to the present definition of the SI second will be 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 will be 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.

Progress beyond the state of the art

This project builds upon the achievements of previous EMRP and EMPIR projects, most recently SIB55 ITOC, 15SIB03 OC18 and15SIB05 OFTEN, to bring optical atomic clocks to the stage where they contribute regularly to TAI – a significant milestone on the path to the redefinition of the SI second.

Unattended uptimes of 80 % – 90 % over several weeks will be achieved for both trapped ion and neutral atom lattice clocks. 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.

The international consistency of optical clocks will be checked through a coordinated programme of frequency comparisons, using both optical fibre links and satellite links. Using optical fibre links, comparison uncertainties for the most advanced optical clocks will be reduced by an order of magnitude or more compared to the state-of-the-art at the start of the project.

Experimental prototypes of UTC(*k*) timescales incorporating optical clocks will be demonstrated, building on preliminary paper studies performed within the SIB55 ITOC project. At the start of the project, no laboratories were using optical clocks as part of their UTC(*k*) timescales, and the first experimental studies in this direction had only recently been started in Japan and the USA.

Up-to-date evaluations of the expanding worldwide body of clock comparison data will be performed, using methods developed within the SIB55 ITOC project, to check the internal consistency of the data and derive optimal values for the frequencies and uncertainties of optical secondary representations of the second. These are required for TAI steering by optical clocks. Compared to the state-of-the-art at the start of the project, lower uncertainties of the optimal frequency values are expected, and correlations will be taken into account for the first time to ensure that the values are unbiased.

By the end of the project, data from European optical clocks in five laboratories will be being submitted to the BIPM on a regular basis. It was only a few months prior to the start of the project that the first optical clock was used for TAI steering, and submission of data is currently sporadic and has a high latency.

Results

Robustness of optical clocks

The robustness of optical clocks is being improved by developing new approaches for automatic long-term control of laser systems and for automated adjustment of optical setups. Both trapped ion optical clocks and neutral atom optical lattice clocks are being addressed. The focus has been on the systems that have been observed to require most frequent user intervention, and a variety of approaches are being tested by different partners within the consortium in order to compare their effectiveness. These will be key to achieving the target of unattended uptimes of 80 % – 90 % over several weeks.

Methods have been developed for automatically relocking lasers to external stabilisation cavities, external enhancement cavities used for second-harmonic generation and enhancement cavities for optical lattices.

Systems are also being developed for automatic laser beam re-alignment into optical fibres and of objectives for ion imaging.

Software to schedule and perform operational checks, e.g. the measurement of environmental parameters necessary to correct for systematic frequency shifts, has been written and is now being tested. Experimental control systems have been extended to enable interleaved measurements to be performed to determine the magnitude of residual frequency shifting parameters. These developments will enable on-the-fly correction of systematic frequency shifts to be performed, to prepare the way for real-time steering of UTC(*k*) timescales and contributions to TAI.

International consistency of optical clocks

A new optical fibre link has been set up from Paris to Turin to extend the reach of the European optical clock network. The section between Paris and Modane on the French-Italian border has been optimised, with characterisation of the noise on the round trip from Paris – Modane – Paris (2000 km in total) demonstrating a robust link with long-term stability and accuracy in frequency at the 10^{-19} level. Checks on the performance of the span from Modane to Turin are in progress. Once optimised, the new link will enable optical clocks in four different European laboratories to be compared at a level commensurate with the performance of the clocks.

Several local optical frequency comparisons have already been performed. Preliminary remote optical clock comparisons were carried out in summer 2019 using the optical fibre links between London, Paris and Braunschweig, which connected optical clocks at three institutions. A larger coordinated programme of frequency comparisons was performed in March 2020, using satellite links in addition to optical fibre links. This enabled more optical clocks to participate in the comparisons, including one from collaborator NMIJ in Japan. For comparisons using optical fibre links, statistical uncertainties in the low 10^{-17} range were achieved. For comparisons via GNSS links, statistical uncertainties were in the low 10^{-16} range. Traceability to the present definition of the second is being ensured by including caesium primary frequency standards in the comparisons performed within the project.

There are significant correlations between the various frequency ratios measured in such coordinated clock comparison campaigns. Guidelines have been prepared on the evaluation and reporting of correlation coefficients, as their proper quantification is essential to avoid overestimating the uncertainty and biasing the recommended frequency values for secondary representations of the second. These guidelines are now being used by all partners and collaborators to compute the correlation coefficients between the various frequency ratios that have been measured.

Optical clocks in UTC(k) timescales

Work is underway to develop, test and optimise algorithms and software for real-time validation of data provided by optical clocks, to prepare the way for steering of experimental prototype UTCx(*k*) timescales. The whole metrological connection between the atomic reference and the flywheel used to generate the timescale is being considered, i.e. frequency combs and local frequency links as well as the optical clocks themselves.

Several approaches have been developed to detect cycle slips or other anomalous behaviour in the links between the atomic reference and the flywheel, and the effectiveness of these is being compared. They have been applied to process the data from the March 2020 campaign, allowing a more efficient and rigorous analysis of the results. Work on the validation of the atomic data is also underway.

Preliminary steering algorithms have also been developed, taking into account realistic experimental inputs, operational parameters and constraints. These have been tested on simulated data and will next be tested on historical datasets before being applied to steer the prototype UTCx(*k*) timescales.

Optical clock contributions to TAI

Two independent software codes for least-squares analysis of frequency comparison data have been written to provide independent verification of results generated using software previously developed within the SIB55 ITOC project. Data from frequency comparison experiments has been collected and added to the input data used in the CCTF 2017 least-squares adjustment. A preliminary least-squares analysis has been performed to check the consistency of the body of data and to derive optimised values for the frequencies and uncertainties of optical secondary representations of the second. Some correlation coefficients have been estimated and early analyses show that correlations from the systematic uncertainties of caesium fountain primary frequency standards (due to multiple measurements with the same fountains) should be carefully considered for an accurate uncertainty evaluation. Optimised values for the frequencies of secondary representations of the second are required for TAI steering by optical clocks.

Guidelines on the submission of optical clock data to the BIPM have been prepared for consortium use. INRIM have submitted data from their Yb optical lattice clock, collected prior to the project start, to the BIPM. Following approval from the WGPSFS, this data appeared in Circular T no. 383 (November 2019) and was used for TAI steering. Several other optical clocks have also been compared with local hydrogen masers over periods aligned with Circular T 5-day reporting intervals, to gather data that will be used for future submissions to the BIPM. Some clocks are being upgraded before collecting more data to enable a lower uncertainty to be achieved.

Impact

Dissemination activities

A project website has been set up to present an overview of the project, together with news updates and announcements. It also provides access to papers, reports and open data produced during the project. The aims of the project and its early results have already been presented by members of the consortium at 31 conferences and workshops. Nine peer-reviewed papers have been published although one is still in the embargo period before it can be made open access. 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 CCTF Working Group on Primary and Secondary Frequency Standards, 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.

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 already 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.

Impact on the metrology and scientific communities

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

The coordinated programme of optical clock comparisons includes six out of eight systems currently recognised as secondary representations of the second, allowing their international consistency and long-term reliability to be assessed. This will help 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 allow the most promising candidates for a future redefinition of the second to be identified.

The measurements and analysis will make significant contributions to improved recommended frequency values for secondary representations of the second, which are expected to be at the limit set by the uncertainties of caesium fountain primary standards. Improvements in 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 will give 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 addresses a future change in the definition and realisation of the SI unit of time, the route to impact will be through the CCTF and its working groups. The consortium is well represented on these bodies, where information on the project progress and outputs will be disseminated through tailored presentations and written reports.

Contributions to the Frequency Standards Working Group (WGFS) will include improved measurements of optical frequency ratios and absolute frequencies for six out of the eight optical clocks currently designated as secondary representations of the second. Several measurements performed in the project were submitted to the WGFS in 2020. The guidelines on handling correlations between individual measurements were also shared with the WGFS and are influencing their approach to updating the list of recommended frequency values they maintain.

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. One optical clock from the consortium was included in Circular T for the first time in November 2019.

Reports on the project outputs will also be presented to other working groups of the CCTF. In particular these are expected to have a significant influence on discussions within the Working Group on Strategic Planning (WGSP). Consortium members are actively participating in a new task force on the roadmap for a redefinition of the second, set up by the WGSP. The work will thus pave the way towards a future choice of primary frequency standard and the redefinition of the SI second.

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, the project is expected to result in widespread impact on innovation, science and daily life.

List of publications

E. Benkler, B. Lipphardt, T. Puppe, R. Wilk, R. Rohde and U. Sterr
"End-to-end topology for fiber comb based optical frequency transfer at the 10^{-21} level"
Optics Express 27, 36886–36902 (2019)

M. Pizzocaro, F. Bregolin, P. Barbieri, B. Rauf, F. Levi and D. Calonico
"Absolute frequency measurement of the $^{1}S_{0} - {}^{3}P_{0}$ transition of ^{171}Yb with a link to International Atomic Time"
[Metrologia 57, 035007 (2020)]

H. A. Fürst, C.-H. Yeh, D. Kalincev, A. P. Kulosa, L. S. Dreissen, R. Lange, E. Benkler, N. Huntemann, E. Peik and T. E. Mehlstäubler
"Coherent excitation of the highly forbidden electric octupole transition in $^{172}Yb^{+}$"
[Physical Review Letters 125, 163001 (2020)]

R. Schwarz, S. Dörscher, A. Al-Masoudi, E. Benkler, T. Legero, U. Sterr, S. Weyers, J. Rahm, B. Lipphardt and C. Lisdat
"Long term measurement of the ^{87}Sr clock frequency at the limit of primary Cs clocks"
[Physical Review Research 2, 033242 (2020)]

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)]

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)]

S. Dörscher, N. Huntemann, R. Schwarz, R. Lange, E. Benkler, B. Lipphardt, U. Sterr, E. Peik and C. Lisdat
"Optical frequency ratio of a $^{171}Yb^{+}$ single-ion clock and a ^{87}Sr lattice clock"
[Metrologia 58, 015005 (2021)]

R. Lange, N. Huntemann, J. M. Rahm, C. Sanner, H. Shao, B. Lipphardt, C. Tamm, S. Weyers and E. Peik
"Improved limits for violations of local position invariance from atomic clock comparisons"
[Physical Review Letters 126, 011102 (2021)]

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1^{st} May 2019 (36 months)	
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Internal Funded Partners: 1. NPL, UK 2. CMI, Czech Republic 3. GUM, Poland 4. INRIM, Italy 5. LNE, France 6. OBSPARIS, France 7. PTB, Germany 8. VTT, Finland	External Funded Partners: 9. BGU, Israel 10. CNRS, France 11. LUH, Germany 12. POLITO, Italy 13. SRC PAS, Poland 14. UMK, Poland	Unfunded Partners:
Linked Third Parties: 15. CNRS, France (linked to OBSPARIS), 16. UP13, France (linked to CNRS)		
RMG1: *ROA, Spain* (Employing organisation); *NPL, UK* (Guestworking organisation) RMG2: *ROA, Spain* (Employing organisation); *OBSPARIS, France* (Guestworking organisation)		