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. However, no optical clock has yet 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 and results

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.

Robustness of optical clocks

Unattended uptimes of 80 % – 90 % over several weeks will be achieved for both trapped ion and neutral atom lattice clocks. This will require new approaches for automatic control and re-locking of laser systems and adjustment of optics, as well as software for automatic scheduling of procedures that currently require human intervention. So far, such high uptimes have 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. Tools will also be developed for on-the-fly correction of systematic frequency shifts to prepare the way for real-time steering of UTC(*k*) timescales and contributions to TAI.

International consistency of optical clocks

The international consistency of optical clocks will be checked through a coordinated programme of frequency comparisons. Using optical fibre links, comparison uncertainties between clocks across Europe will be reduced by an order of magnitude or more for the most advanced optical clocks, and the European fibre network linking NPL, OBSPARIS and PTB will be extended to include INRIM. Satellite links will be used to include more optical clocks in the comparisons, opening up the possibility of involving state-of-the-art clocks from organisations outside Europe. Traceability to the present definition of the second will be ensured by including caesium primary frequency standards in the comparison programme.

Optical clocks in UTC(k) timescales

Methods will be demonstrated for incorporating optical clocks into UTC(*k*) timescales, building on preliminary paper studies performed within the SIB55 ITOC project. Software routines will be developed for real-time validation of optical clock data and simulations will be performed to test and optimise timescale steering algorithms, taking into account realistic operational parameters and constraints. These algorithms will subsequently be employed in experimental prototypes, the stability of which will be evaluated by direct comparison as well as by comparison to standard UTC(*k*) timescales and UTC. No laboratories are yet using optical clocks as part of their UTC(*k*) timescales, and only recently were the first experimental studies in this direction started in Japan.

Optical clock contributions to TAI

Up-to-date evaluations of the expanding worldwide body of clock comparison data will be performed, using methods developed within the SIB55 ITOC project, and taking full account of correlations. In this way the internal consistency of the data will be checked, and optimal values derived for the frequencies and uncertainties of optical secondary representations of the second. These are required for TAI steering by optical clocks.

Data from at least one optical clock in each of five European laboratories will be submitted to the BIPM to be considered for inclusion in the bulletin Circular T. By the end of the project, data from these optical clocks will be being submitted to the BIPM on a regular basis.

Impact

Impact on industrial and other user communities

The techniques and hardware 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. 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.

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. Together with new guidelines on handling correlations between individual measurements and our least-squares analyses of the worldwide body of available clock comparison data, this is expected to have significant input to the list of recommended frequency values maintained by this working group.

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.

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), which is responsible for updating as necessary the international roadmap towards a future redefinition of the SI second. 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.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1st May 2019 (36 months)</td></tr>
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<tr><td>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</td><td>External Funded Partners:
9. BGU, Israel
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11. LUH, Germany
12. POLITO, Italy
13. SRC PAS, Poland
14. UMK, Poland</td><td>Unfunded Partners:</td></tr>
<tr><td colspan="3">RMG:</td></tr>
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