22IEM01 TOCK

Publishable Summary for 22IEM01 TOCK
Transportable optical clocks for key comparisons

Overview

In recent years, significant progress with optical clocks has been achieved, such that they clearly outperform current primary standards of time and frequency. The currently established key comparison for time and frequency uses satellite-based techniques to provide international consistency with 10^{-16} fractional uncertainty. Optical fibre links between a few NMI laboratories in Europe are available and can enable clock comparisons with low 10^{-18} uncertainty, but these are limited by relativistic effects. To overcome these limitations and to compare optical clocks that cannot be interconnected via optical fibre links, this project will develop travelling frequency standards with performance exceeding the current state-of-the-art. The use of these transportable optical clocks (TOCs) as frequency standards will be evaluated by the project and their feasibility for use in future key comparisons will be demonstrated.

Need

The fundamental properties of atoms provide characteristic microwave or optical frequency references used in atomic clocks to realise the most precise measurement devices available today. Within the SI system of units, the realisation of the unit of time with Caesium atomic clocks plays an essential role, as the unit second is contained in the definition of 6 of the 7 base units via the defining constants. Having highly accurate, stable, and reliable reference frequency standards is a pre-requisite not only for the SI System of Units, but also for many everyday technologies that rely on precise time keeping such as banking transactions, communication, and navigation.

Due to the higher reference transition frequency, highly precise optical clocks have made great progress with a variety of different reference systems with neutral atoms and single ions. The established methods for international key comparison in time and frequency currently use satellite-based techniques. However, satellite-based techniques have a clear limitation for comparisons of these high-performance clocks and are unable to take full advantage of the future redefinition of the unit of time. To overcome these limitations, travelling frequency standards with performance exceeding the current state-of-the-art need to be developed, evaluated, and tested for use in future key comparisons. This is particularly urgent given the growing needs in global communication and navigation.

TOCs also need to be developed to provide accurate and stable frequency references outside NMIs and DIs for example at specialised research facilities, for geodetic base stations or in future telecommunications and navigation systems. Thus, the research in this project will address the need for advanced techniques for providing traceability for measurements to the users of metrology services.

Objectives

The overall goal of this project is to develop an integrated European metrology infrastructure for the development and deployment of highly stable and accurate TOC systems. The specific objectives of the project are:

1. To develop and to demonstrate the performance of commercially unavailable components of TOC systems (e.g., ultra-stable laser, optical bench for atom/ion cooling, trapping and interrogation, UHV physics package for atom/ion clock) capable of operation within 5 days after transportation.

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2. To develop TOCs that demonstrate short-term frequency instabilities below $\mathbf{5} \times \mathbf{10^{-15}}\sqrt{\boldsymbol{\tau}(\boldsymbol{s})}$ and a systematic uncertainty equal or below $\mathbf{5} \times \mathbf{10^{-18}}$.
3. To evaluate the TOCs by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the TOC for investigation of possible errors.
4. To demonstrate the feasibility of future key comparisons using TOCs as an alternative to established time and frequency key comparisons performed via satellite-based techniques.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs), international metrology committees (e.g. CIPM Consultative Committee for Time and Frequency (CCTF)) and end users (research facilities in geodesy, space and physics, telecommunications and aerospace enterprises, scientific and precision instrumentation manufacturers).

Progress beyond the state of the art

This project builds upon the achievements of previous EMRP and EMPIR projects, most recently 18SIB05 ROCIT and 20FUN01 TSCAC. In 20FUN01 TSCAC fundamental aspects of the future realisation of composite optical clocks based on two atomic species is being investigated and in 18SIB05 ROCIT the robustness of established optical clock systems was improved, and their application for the steering of international timescales was demonstrated. This project is building upon these results and focussing on the development and deployment of highly stable and accurate TOC systems and investigate their use in future key comparisons for time and frequency.

To develop and demonstrate the performance of commercially unavailable components of TOC systems

TOCs have special requirements for their components; they need to be capable of withstanding transportation and thus have higher demands on weight, size and power consumptions, whilst a similar performance to their stationary counterparts in a laboratory environment is needed. In particular, operation shortly after transportation (i.e. within 5 days) is often needed for TOCs. Some of the required components for TOCs have been made commercially available, however, so far commercially unavailable components include ultra-stable laser, optical benches for atom/ion cooling, trapping and interrogation and UHV physics packages for atom/ion clock. These components not only need developing but their proper operation within 5 days after transportation also needs to be verified. This project is going beyond the current state of the art by developing and verifying such unavailable components for TOCs. In this way, key components will be made available for the first time for prototypes and can be used for later commercialisation by industry stakeholders.

To develop TOCs that demonstrate short-term frequency instabilities below $\mathbf{5} \times \mathbf{10^{-15}}\sqrt{\boldsymbol{\tau}(\boldsymbol{s})}$ *and a systematic uncertainty equal or below* $\mathbf{5} \times \mathbf{10^{-18}}$

So far only, a few TOC prototypes have been realised worldwide, with the most advanced system realised in Japan demonstrating mid 10^{-18} uncertainty. In Europe, first prototypes of TOCs have been realised, but their uncertainty has been larger than 10^{-17} so far. Within this project, new systems are being developed and existing TOCs improved with the aim of reaching frequency instabilities below $\mathbf{5} \times \mathbf{10^{-15}}\sqrt{\boldsymbol{\tau}(\boldsymbol{s})}$ and systematic uncertainties equal or below $\mathbf{5} \times \mathbf{10^{-18}}$. The project is going beyond the state of the art and focussing on the development of physics packages that enable operation with low frequency instability as well as the investigation of systematic frequency shifts for the specific operational conditions of TOCs. This work will increase the number of available TOCs in Europe and significantly strengthen Europe's measurement capabilities.

To evaluate the TOCs by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the TOC for investigation of possible errors.

Only a handful of measurements involving TOCs have been reported in current literature, and only in a single case has an uncertainty below 10^{-17} been achieved. This clock comparison was against another system that was almost identical meaning that some systematic shifts were common-mode. To prevent unobserved systematic effects, within this project, TOCs are being evaluated and compared to stationary systems that differ significantly in their design from the TOCs. In this way, a detailed assessment of the frequency stability and the systematic uncertainty of the TOC can be performed. In addition to this, the project will investigate the limitations related to transportation, by repeating procedures after real or simulated transportation. This repeated evaluation will enable the compilation of guidelines for the re-evaluation of operation parameters of TOCs after transportation and how TOC performance can best be retrieved after transportation.

To demonstrate the feasibility of future key comparisons using TOCs as an alternative to established time and frequency key comparisons performed via satellite-based techniques.

Across Europe a few NMIs and DIs are interconnected using dedicated optical fibre links that enable frequency comparisons with low 10^{-18} uncertainty, that is limited by relativistic effects. To overcome these limitations and go beyond the current state of the art, this project will compare optical clocks that cannot be interconnected via optical fibre links and demonstrate the use of travelling frequency standards in future key comparisons in time and frequency. For these comparisons, the project will perform complementary measurements over existing fibre links in order to maximise the impact of each campaign and to mitigate the risk of a failure of the stationary clock system.

Results

Objective 1: to develop and demonstrate the performance of commercially unavailable components of TOC systems.

The project is currently developing commercially unavailable components including ultra-stable laser, optical benches for atom/ion cooling, trapping and interrogation and UHV physics packages for atom and ion clocks. As part of this, existing setups are being improved and new vacuum chambers have been designed. For ion-based clocks ion traps coating of the electrodes and for neutral atom clocks atom cooling is being investigated. For transportable clocks laser stabilisation is crucial, therefore, setups for this and their distribution has been prepared and will subsequently be set up.

Objective 2: to develop TOCs that demonstrate short-term frequency instabilities below $\mathbf{5} \times \mathbf{10^{-15}}\sqrt{\boldsymbol{\tau}(\boldsymbol{s})}$ and a systematic uncertainty equal or below $\mathbf{5} \times \mathbf{10^{-18}}$.

The project is working on improving the loading and trapping conditions for ion-based clocks, in order to ensure reliable long-term operation. Furthermore, components will be combined to set up TOCs demonstrating the expected performance in a later part of the project. For existing clock setups, work is focussed on ways to improve both the instability and systematic uncertainty. While for reduced instability short preparation periods and long interrogation times are essential and have been focussed on by the project. The systematic uncertainty can also be reduced by an improved evaluation of the leading shift effects such as perturbing thermal radiation as well as other perturbing electric and magnetic fields.

Objective 3: To evaluate the TOCs by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the TOC for investigation of possible errors.

So far, the project has performed first comparisons between TOCs with stationary systems in order to assess the estimated uncertainty of the systems and to verify their instability. For an ion-based system an instability of $6 \times \mathbf{10^{-15}}\sqrt{\boldsymbol{\tau}(\mathbf{s})}$ was observed and very good agreement with the stationary system. A much lower instability of below $5 \times \mathbf{10^{-16}}\sqrt{\boldsymbol{\tau}(\mathbf{s})}$ was observed for a TOC based on neutral atoms in an optical lattice. These components not only need developing further but their proper operation within 5 days after transportation also needs to be verified. This project will go beyond the current state of the art by developing and verifying such unavailable components for TOCs. In this way, key components will be made available for the first time for prototypes and can be used for later commercialisation by industry stakeholders. Within the consortium the TOCs are currently being prepared for comparisons against between participants laboratory systems. This includes the setup of the necessary infrastructure at different participants laboratories.

Objective 4: *To demonstrate the feasibility of future key comparisons using TOCs as an alternative to established time and frequency key comparisons performed via satellite-based techniques.*

Currently, preparations are under way for the first clock comparison campaigns after transportation of TOCs. This includes (i) preparatory work at the involved participants, (ii) work on the optical fibre links that will enable an increase of the number of remote optical clocks and (iii) a discussion of data formats.

Outcomes and impact

The project has set-up a website at https://www.ptb.de/epm2022/tock/ to promote the project to stakeholders. The project has also been promoted via 2 media articles by partner VTT https://yle.fi/a/74-20051993 and https://yle.fi/a/74-20059025

In conjunction with the kick-off meeting of this project, a stakeholder workshop was held in hybrid format together with the EMPIR project 20FUN01 TSCAC. Presentations were given that demonstrated the outcomes from 20FUN01 TSCAC and the plans for this project 22IEM01 to approx. 50 participants from industry and the scientific community. The results of this project will be presented in a second similar workshop which will be held towards the end of this project.

Outcomes for industrial and other user communities

The techniques and hardware developed for TOCs within this project will benefit research groups and industrial organisations developing portable/transferable optical clocks for use in field applications. The outcome of the project may also lead to new ideas for improving the robustness of laboratory optical clocks. The clocks developed within the project will become role models for optical clock development at industrial stakeholders. A number of components for TOCs are commercially available, however, there are still many commercially unavailable components (e.g. ultra-stable laser with 10^{-16} fractional instability, optical benches for atom/ion cooling) and this project will develop verify these currently unavailable TOC components so that complete systems can become commercially available for applications including geodetic height measurements, synchronisation of telecommunications networks and future satellite navigation systems. Applications of such clock subsystems can also be extended by industry to other areas such as precision spectroscopy and quantum information processing. Moreover, industrial development of optical and electronic systems will be supported by via the project's production of good practice guidance on (i) the-state-of-the-art optical clocks and key technical aspects on the integration of optical clocks and (ii) optical clock time and frequency comparison techniques. Further to this the project has so far identified and involved 8 industrial stakeholders in project workshops and lectures and engage them via social media channels.

Outcomes for the metrology and scientific communities

This project will investigate new ways to perform key comparisons for time and frequency using highly stable and accurate TOC systems. The development and deployment of such new TOCs will improve the accuracy with which distant clocks can be compared and thereby supports the selection of suitable reference systems for a redefinition of the SI second, an essential contribution to fundamental metrology and to the long-term development of the SI system of units.

It is intended that a collaborator will be invited to project meetings to foster scientific knowledge exchange with the stakeholder community in the field of geodetic measurements. This will also be used to inform the consortia of the most recent advances in geodesy and potential use of clock comparisons involving TOCs. So far 11 key stakeholders from the metrology and scientific communities have been identified.

The project's results should also benefit fundamental physics, e.g., comparisons between optical clocks with verified uncertainties can be used to set limits on possible present-day variations in fundamental physical constants, to test the predictions of special and general relativity and to search for dark matter candidates.

The project's production of 2 good practice guides, will also benefit the metrology and scientific communities. Further to this the project will disseminate its outcome to the metrology and scientific communities via project workshops, lectures, conferences, open access publications and a summer school for young researchers.

So far, the project has engaged with the scientific community via 3 tutorials on (i) Optical clocks, (ii) Highly Charged Ion Clocks, and (iii) Quantum Logic Spectroscopy. The project has also supported an PhD thesis on 'A highly stable UV clock laser'.

The consortium has also presented the project 16 times (as posters or presentations) at conferences such as ICOLS 2023 (International Conference on Laser Spectroscopy), EQTC 2023 (European Quantum Technologies Conference), 9FSM 2023 (the 9th Symposium on Frequency Standards and Metrology) and IEEE IFCS-EFTF 2023 (Joint Conference of the IEEE International Frequency Control Symposium and the European Frequency and Time Forum).

Outcomes for relevant standards

The project has already been present to CIPM's CCTF Task force for the redefinition of the second SG1. The project investigates alternatives to the established key comparison for time and frequency, thus the main impact in standardisation will be through the CIPM's CCTF and its working groups; the Frequency Standards Working Group (WGFS), Working Group on Primary and Secondary Frequency Standards (WGPSFS) and Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WGATFT). The consortium is well represented on these bodies, where information on the project progress and outputs will be disseminated through presentations and reports. In particular, the project's report on the feasibility of future key comparisons using transportable optical clocks as an alternative to established time and frequency key comparisons performed via satellite-based techniques, is expected to impact the list of recommended frequency values maintained by CCTF's working groups.

Reports on the project outputs will also be presented to other working groups of the CCTF, such as WGSP, which is responsible for updating as necessary the international roadmap towards a future redefinition of the SI second. Further to this the project will provide input to EURAMET Technical Committee on Time and Frequency (TC-TF), which is responsible for the cooperative structure of time and frequency metrology laboratories in Europe.

Longer-term economic, social and environmental impacts

The longer-term impact of this project will result from the pivotal role of atomic clocks in the future revisions of SI units and in several growing technology sectors. The project's results will support the international metrological community in their decisions towards a future redefinition of the SI second. Improved techniques to compare atomic clocks and the development of TOCs are also relevant for technological applications, in sectors such as navigation, space, aerospace, telecommunications and energy networks. Further to this, TOCs have the potential to support future miniaturisation of payloads on onboard satellites and aerospace vehicles, and to support geodesy with cm-level precision and applications in climate research.

Project start date and duration:	1 May 2023, 36 months	
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