Publishable Summary for 15SIB03 OC18
Optical clocks with 1 × 10^{-18} uncertainty

Overview

This project has made significant advances in the performance of optical atomic clocks across Europe, to support the ongoing work towards a redefinition of the SI second. World-leading developments from this project in laser frequency stabilisation and atom trapping have brought about improvements in both the accuracy and stability of the clocks. This measurement capability enables the clocks to generate optical frequencies with reduced uncertainty for end users in metrology and industry. The clocks have also been used for scientific measurements that test the laws of fundamental physics at unprecedented levels.

Need

There has been a need for optical clocks with fractional frequency uncertainty at the 10^{-18} level from a wide range of sectors including basic science and metrology to applications in geodesy, satellite navigation and environmental monitoring.

It has been anticipated in the metrology community that there will be an international decision to redefine the SI second in terms of an optical standard, since optical clocks have already been shown to outperform the caesium primary standards by more than an order of magnitude. Before a redefinition can be made, however, there must be confidence that the optical clocks actually perform at the level they are estimated to achieve. Measurements must therefore be carried out to validate the performance, using the highest accuracy clocks available. Tests of fundamental science, such as looking for violations of Einstein's Equivalence Principle, also require high-accuracy clocks to set tighter constraints on physical theories. There is therefore a need for fractional frequency uncertainties arising from systematic shifts to reach down to the 10^{-18} level.

For statistical uncertainties to reach the same level, the frequency output from optical clocks must be averaged over a period of time. A barrier to industry using optical clocks 'in the field' has been that the necessary averaging time was of the order of days or weeks. For geodesy applications such as monitoring changes in ocean currents or surveying for gas and oil, much shorter averaging times are required. To reach statistical uncertainties of 10^{-18} after just a few hours, laser frequency instabilities need to be at or below 10^{-16} at 1 s. New atom traps that can support long coherent probe times (> 1 s) are also needed so that frequency instability is not degraded when probing the atoms.

Objectives

The main aim of this project is to develop world-leading optical atomic clocks across Europe, which will support a future redefinition of the SI second and underpin international time scales.

1. To achieve instabilities in laser frequencies of 1 x 10^{-16} or below after 1 s, by investigating: (a) room temperature glass cavities, (b) cryogenic silicon cavities (c) spectral hole burning and (d) active resonators. Guidelines will be written to show how this stability can be transferred from the laser source to the atoms in optical clocks whilst adding no more than 1 x 10^{-17} to the laser noise after 1 s.
2. To develop traps for single ions and neutral atoms that support > 1 s probe times. Guidelines will be written for an optimised design of ion trap; for neutral atoms a report will be written summarising the effects of collisions, photon scattering and parametric heating on coherence times.
3. To evaluate and reduce systematic uncertainties in optical clocks to the level of 10^{-18}. A report will be written summarising improved control and measurement of the thermal environment in single ion and neutral atom optical clocks, leading to 10^{-18} uncertainties in blackbody radiation shifts for clocks operating at both cryogenic and room temperatures. An uncertainty report for controlling and

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evaluating lattice light shifts and collisional shifts at the 10^{-18} level in neutral atom optical lattice clocks will also be written.

4. To implement novel interrogation methods in optical clocks that use an optimised sequence of probe pulses to reduce even further the instability and inaccuracy of the clocks. To validate performance with target uncertainty 1 x 10^{-18}, through direct measurement of the frequency difference between two independent clocks.
5. To facilitate the uptake of the technology by the measurement supply chain and end users by making optical frequency standards more practical and accessible to end users.

Progress beyond the state-of-the-art
The optical clocks developed during the project made significant progress, with half of the clocks achieving at least a four-fold improvement in the estimated accuracy of their frequency output. Comparisons between the outputs of two independent ytterbium ion clocks were carried out over several months to verify their accuracy and the demonstrated agreement was at the low 10^{-18} level, which is a world-leading result for ion clocks.

As well as measuring optical frequency ratios that are of metrological importance, the clocks were also used to make advances in fundamental science. Tests of special relativity were carried out with twice the sensitivity previously achieved, searches for dark matter were carried out with several orders of magnitude better resolution and new limits were placed on Lorentz symmetry violation parameters.

To improve the performance of the clocks, many advances were made, including: a new state-of-the-art in laser frequency stabilisation, new traps for ions and neutral atoms with improved temperature control, advanced probing techniques, and better understanding of lattice light shifts and collisional effects between atoms. Many of these advances were firsts in Europe and several have also been world-leading.

Results

Objective 1 – to achieve instabilities in laser frequencies of 1 × 10^{-16} at 1 s and to transfer this to the atoms whilst adding no more than 1 x 10^{-17} to the laser noise after 1 s.
[Target: achieved]

Ultrastable lasers are a key component in optical atomic clocks. They serve as the interrogation laser for atomic clock transitions and largely determine the stability of the clocks. This project investigated the performance that could be achieved by stabilising lasers to room-temperature glass cavities and demonstrated frequency instabilities of 10^{-16} after 1 s [Didier2019]. Cavities made of single-crystal silicon, operated at a temperature of 124 K, were also investigated and reached a frequency instability of 4 × 10^{-17} [Matei2017]. This is a new state-of-the-art and a factor of two beyond the best previously reported results. Further investigations were then carried out at even colder temperatures of 4 K [Zhang2017], where vibrations from the cryo-cooler are a much greater technical challenge. In parallel, novel laser stabilisation techniques that rely on atomic transitions to set the frequency reference rather than optical cavity lengths were also explored: spectral hole burning [Gobron2017] and active resonators [Schäffer2017]. Results from these new techniques, which are still in their infancy, demonstrated laser frequency instabilities of ~ 1 × 10^{-15} at 1 s.

Techniques to transfer the frequency stability from one wavelength to another with optical frequency combs added no more than 8 x 10^{-18} at 1 s to the laser noise. It was also shown that the technical sources of noise that could affect the spatial transfer of light along the propagation path could be controlled at the 10^{-17} level or below at 1s, including spatial transfer via phase-noise-compensated optical fibres [Rauf2018].

Objective 2 – to develop traps for single ions and neutral atoms that support > 1 s probe times.
[Target: achieved]

Long probe times are desirable in optical atomic clocks as this enables the best possible resolution of the atomic feature that is used to stabilise the optical frequency output of the clock. The maximum possible probe time is generally limited by either the loss of atoms from the trap, or else the loss of coherence in the atom-light coupling. These effects must therefore be characterised and controlled in the atom traps.

The dominant mechanism of atom loss from a trap is due to collisions with room-temperature background gas. Before the start of this project, very little was known about the details of background gas collisions on *cold,* trapped atoms as previous studies had mostly focussed on background gas collisions with room-temperature atomic samples. The theoretical studies in this project [Cybulski2019] found not only the loss rate of cold atoms from the trap as a function of vacuum pressure, but also the size of collisional frequency shifts.

For neutral atoms trapped in an optical lattice, atomic decoherence can arise from the scattering of lattice photons. This effect was investigated in neutral Sr and the scattering rate was compared to that of spontaneous decay out of the clock's upper state, which was also measured for the first time in this project [Dörscher2018]. It was found that, at typical lattice depths, scattering does not prevent > 1 s probe times. For single-ion clocks, the maximum useful probe time can be limited by motional heating of the ion. New ion traps were developed within this project, and a new state-of-the-art was achieved in the motional heating rate of single ions in an end-cap style trap. Probe times of > 1 s were successfully demonstrated.

Objective 3 – to evaluate and reduce systematic uncertainties in optical clocks to the level of 10^{-18}
[Target: achieved]

All sources of systematic frequency shifts that can affect optical clocks need to be well understood and controlled to achieve fractional frequency uncertainties down to the level of 1×10^{-18}. The dominant contributions to frequency uncertainty prior to the project were identified to come from: (i) blackbody radiation (BBR) shifts from the atoms' thermal environment, (ii) light shifts from the optical lattice in neutral atom clocks and (iii) collisional shifts resulting from the collisions between atoms trapped in a lattice.

For the blackbody radiation shift, the project results demonstrated that sufficient control could be gained over the thermal environment to contribute no more than 10^{-18} to the fractional frequency uncertainties for both neutral atom and single-ion clocks. Techniques included a room-temperature vacuum chamber with thermal shielding which was a first for Europe, and a new design of cryogenic system. Designs were assisted by finite element modelling and characterisation of material emissivities, and the experimental measurements on the resulting systems showed excellent agreement with the finite element models.

Studies of lattice light shifts and collisional shifts revealed that these effects could also be controlled with fractional frequency uncertainties at the 10^{-18} level. Experimental studies in both Sr and Yb clocks showed that this uncertainty could be achieved even for moderate trap depths. The theory associated with the collisional shifts led to two orders of magnitude improvement in the uncertainty of s-wave scattering lengths for Yb atoms [Borkowski2018a], and also resulted in a novel proposal for a lattice clock based on weakly bound molecules [Borkowski2018b].

Objective 4 – to implement novel interrogation methods and to validate performance with target uncertainty 1 x 10^{-18}
[Target: achieved]

The statistical and systematic uncertainties in the clocks were further reduced by applying carefully tailored sequences of probe pulses to the atoms. A theoretical study, taking into account common laser noise processes, revealed the optimum probe pulse times to use in atomic clocks to minimise frequency instabilities for each type of laser noise [Leroux2017]. In experimental studies, the first demonstration in Europe of an optical lattice clock being operated with a 50% duty cycle [Vallet2017] was made while working towards the reduction of clock instability from the Dick effect. A novel 'autobalanced Ramsey' probing sequence [Sanner2018] was also demonstrated to suppress frequency shifts induced by probe pulses and has already been adopted by two independent research groups outside the consortium.

To validate clock performance, the frequency outputs from two independent ytterbium ion optical clocks were compared over several months. The frequency difference corresponded to $2.8(4.2) \times 10^{-18}$, which is not only consistent with the estimated uncertainty budgets of the two clocks, but is also world-leading: never before have two ion clocks been demonstrated to agree with such a small uncertainty. Further details of this clock-clock comparison were published in Nature [Sanner2019].

Impact

Dissemination and engagement

This project has tackled an ambitious programme of research and published 25 papers in peer-reviewed journals including Metrologia, Physical Review Letters and Nature. The work has been included in more than 100 presentations at international conferences as well as in articles for the popular press, and further engagement with the public has taken place at exhibitions and outreach events. Training opportunities specific to this project have included Researcher Mobility Grants totalling 31 months and a School on Optical Clocks in September 2018, which brought together invited speakers and students for a week of lectures, poster sessions, and interesting discussions.

Impact on metrology and relevant standards

This project has improved the performance of optical atomic clocks across Europe in terms of both accuracy and stability, with the most direct impact for the metrology community being on the top-level realisation of the SI second.

The primary frequency standard, upon which the SI second is currently defined, is based on ^{133}Cs. There are also eight optical frequency standards that are accepted as secondary representations of the SI second, and five of them were included in this project: ^{87}Sr, ^{171}Yb, ^{88}Sr^{+}, ^{171}Yb^{+}(E2) and ^{171}Yb^{+}(E3). Improved performance of these clocks therefore leads to smaller uncertainties in the secondary representations of the SI second. Frequency measurements from the clocks are disseminated to a range of standards and technical committees, including the Frequency Standards Working Group of the Consultative Committee for Time and Frequency (CCTF-WGFS) that makes recommendations on updating values for the secondary representations of the SI second. During this project, two new absolute frequency values were measured [Pizzocaro17, Baynham18] and many more are planned for the new project 18SIB05 ROCIT, benefiting from the reduced uncertainties that have been achieved in this project.

Beyond the improvements to the secondary representations, it is anticipated that the SI second will itself be redefined in the future, based on an optical frequency standard. The knowledge accumulated in this project, along with the validated results of clock performance, will therefore influence the international decision to choose the optimum atomic clock species for a future redefinition of the second.

Impact on the scientific communities

Beyond metrology, this project has also benefited the scientific community, through the introduction of new techniques as well as the ability to carry out fundamental physics with the clocks themselves.

An example of this project introducing new techniques is the ‘autobalanced Ramsey’ probing scheme that was developed in objective 4 [Sanner2018]. It proved so successful at suppressing frequency shifts induced by probe pulses that it has already been taken up by two independent research groups outside the consortium: one in France and one in the USA.

For fundamental physics, optical clocks operating at the highest precision can test the laws of physics with unprecedented sensitivity. During this project, such experiments have included tests of special relativity with twice the sensitivity ever achieved before [Delva2017], searches for dark matter with several orders of magnitude better resolution [Wcisło 2016, Wcisło2018] and new limits on Lorentz symmetry violation parameters that improve on previous limits by two orders of magnitude [Sanner2019].

Impact on industrial and other user communities

Objectives 1 and 2 improved clock stability, thus reducing the averaging time needed to reach a given statistical uncertainty. This makes optical clocks more practical for ‘in the field’ measurements. Examples of end users we have been working with that could benefit from low uncertainty optical clocks include radio astronomers needing to synchronise arrays of telescopes in very long baseline interferometry [Krehlik2017], and surveyors needing high spatial and temporal resolution of gravity potentials [Mehlstäubler2018].

To facilitate end users building up new systems, this project has created a set of practical guidelines, detailing the technical requirements for developing optical clocks with 1×10^{-18} uncertainty. It has drawn on the collective knowledge gained across the objectives and is complementary to reviews of scientific advances that are already available in the published literature. The guidelines have been made publicly available on the arXiv (https://arxiv.org/abs/1906.11495) and the project webpage and will be submitted to EURAMET TC-TF for consideration as a Technical Guide.

The consortium has also been working with industrial organisations in a high-profile project ('Opticlock' - separately funded) to build a demonstrator optical clock, based on single trapped ions, with a view to commercialisation. One of the ion traps designed in objective 2 of this project has demonstrated excellent properties and the Opticlock project will now adopt this ion trap in its systems, thus providing a route for its uptake and exploitation into the commercial market.

Longer-term economic, social and environmental impacts

Precision frequency and timing information is at the core of many technologies upon which society increasingly relies. For example, global navigation satellite systems depend on a constellation of highly precise atomic clocks to provide accurate position and timing information. Improvements in clock performance could therefore enable better navigation in the future. Similarly, better timing signals at the heart of telecommunications systems could result in increased network resilience and lower operating costs; synchronised monitoring of weaknesses in energy networks could enable power to be transferred more efficiently. Improved atomic clocks are therefore likely to bring significant benefits, not just to the level of these services but also by stimulating growth in new applications across a broad range of industries.

In the longer term, the high spatial and temporal resolution of gravity potentials that can be measured with optical clocks is expected to have a large environmental benefit. Data gathered from optical clocks over long timescales could allow monitoring of seasonal and long-term trends in ice sheet masses, ocean current transport and overall ocean mass changes. Such data provides critical input to the models which are used to study and forecast the effects of climate change.

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<tr><td colspan="2">Project start date and duration:</td><td>1st May 2016 (3 years)</td></tr>
<tr><td colspan="3">Coordinator: Dr Rachel Godun, National Physical Laboratory, UK
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Project website address: www.OC18.eu</td></tr>
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1 NPL, United Kingdom
2 CMI, Czech Republic
3 INRIM, Italy
4 LNE, France
5 OBSPARIS, France
6 PTB, Germany
7 TUBITAK, Turkey
8 VTT, Finland</td><td>External Funded Partners:
9 KU, Denmark
10 LUH, Germany
11 UMK, Poland</td><td>Unfunded Partners:</td></tr>
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RMG2: ROA, Spain (Employing organisation); INRIM, Italy (Guestworking organisation)</td></tr>
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