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

Overview

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 timescales. The target is to be able to determine the frequency output (or 'tick' rate) of the clocks to an accuracy of 1 part in 10^{18} after just a few hours of statistical averaging.

Need

Optical clocks with 1 x 10^{-18} uncertainty are needed by a wide range of sectors from basic science and metrology to applications in geodesy, satellite navigation and environmental monitoring.

It is anticipated 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 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 physics, such as looking for violations of Einstein's Equivalence Principle, also require clocks with 1 x 10^{-18} accuracy to set an order-of-magnitude tighter constraint on physical theories. Uncertainties in the clock frequency arising from systematic shifts must therefore be evaluated and reduced 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 using optical clocks 'in the field' can be that the necessary averaging time is 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, the optical clock must have laser instabilities at or below 10^{-16} at 1 s transferred to the atoms and a coherent probe time of at least 1 s.

The challenges that must be overcome to reach 1 x 10^{-18} uncertainty are common to the two different types of optical clock being studied: neutral atoms in optical lattice traps and single ions in radio frequency traps. The following objectives will therefore be jointly addressed:

Objectives

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 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 1×10^{-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 SI second is currently realised with Cs fountain atomic clocks, the best of which have accuracies of $1 - 2 \times 10^{-16}$, which represents the level at which their frequency agrees with the unperturbed atomic transition. Optical clocks have already been shown to surpass this performance but, to date, only a small number of optical clocks has been evaluated with uncertainty below the level of 1×10^{-17}. Furthermore, these evaluations have largely been based on estimates; there has been very little direct experimental verification that the clocks actually operate within the stated uncertainties. This project is developing clocks that go beyond the previous state-of-the-art and firmly establishing their uncertainty in the 10^{-18} range through direct measurements. This requires advances in all aspects of the optical clocks: laser stabilisation, atomic traps and control of systematic frequency shifts. A combination of iterative advancements and exploration of novel techniques is being employed. Progress during this project in many of these aspects has already produced results beyond the previous state-of-the-art, as detailed in the section below and the corresponding publications.

Results

Laser frequency stabilisation

This project has demonstrated a new state-of-the-art in laser stabilisation, achieving fractional frequency stabilities of 4×10^{-17} at 1 s. This was achieved by locking a laser to a resonant optical frequency mode of a cryogenic silicon cavity, held at 124 K [1]. Further work has now demonstrated pushing the cavity temperature down to 4 K [2] to reduce the thermal noise floor but, even so, it is expected that it will be difficult to improve optical cavity techniques significantly beyond this and so novel laser stabilisation techniques are also being explored to reach towards 10^{-18} at 1 s. Two of these new techniques (spectral hole burning and active resonators) have already led to encouraging initial results [3, 4]. In parallel, techniques to transfer the stability to the atoms are also being characterised and improved to ensure they do not add more than 1×10^{-17} at 1 s to the laser noise. These include frequency transfer using a femtosecond comb, and spatial transfer via phase-noise-compensated optical fibres [5].

Atom traps

To take advantage of the improved laser stabilities, atomic traps for both single ions and neutral atoms are being designed to support > 1 s coherent probe times. Prototype ion traps of new designs are testing different aspects of the geometry, materials and fabrication processes. The motional heating rate of the ion is being measured as a key parameter in determining the suitability of the trap for long coherent probe times. An optimised design will be produced, informed by the results from the different prototypes. For neutral atoms trapped in optical lattices, theoretical models have yielded initial estimates for the atom loss rates, frequency broadening and shifts arising from collisions between clock atoms and thermal background gases in the vacuum systems. The effects of photon scattering on coherence times have been characterised experimentally [6] and upper limits have been determined on the acceptable depth of the optical lattice trapping potential for Sr atoms. Spectroscopic results will ultimately demonstrate the coherence times achieved.

Systematic uncertainties

The frequency shifts arising from blackbody radiation, lattice light shifts and collisional shifts will all be controlled to an uncertainty at the 10^{-18} level. To suppress uncertainties from blackbody radiation, the surface emissivities of materials used in room-temperature vacuum chambers (Al, Cu, Ti and steel) have been measured, and a variety of temperature sensors is being characterised. This will enable better knowledge of the temperature environment for the atoms. Cryogenic systems have also been designed and are now being built since working at lower temperatures reduces the frequency shift from thermal radiation and hence relaxes the constraints on temperature uncertainty. To understand the frequency shifts arising from collisions between atoms trapped within optical lattice potentials, theoretical studies have been carried out, advancing knowledge of scattering between Yb atoms by two orders of magnitude beyond the previous state-of-the-art [7]. Lattice light shifts have also been studied experimentally by observing the frequency shifts that arise from different intensity optical lattices.

Novel interrogation methods and validating performance

The statistical and systematic uncertainties in the clocks have been 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 [8]. In experimental studies, a novel 'auto-balanced Ramsey' probing sequence [9] demonstrated immunity to a wide variety of frequency shifts induced by probe pulses, and statistical uncertainties in lattice clocks will be reduced by probing two atomic ensembles, each with a 50% duty cycle [10], and interleaving to create a zero dead-time clock.

Two independent ytterbium ion optical clocks have been confirmed to be operating at the low 10^{-18} level of frequency uncertainty, following an extended comparison between them. Direct measurements such as these give much greater confidence in the clock performance than estimated uncertainties, which are more commonly evaluated.

Impact

This is an ambitious programme of research, which is generating many peer-reviewed publications. There will be a strong impact on metrology as the reduction in the optical clock uncertainties is expected to support a future redefinition of the SI second in terms of an optical frequency. Beyond metrology, the high stability and accuracy offered by the optical clocks will benefit measurements in the scientific community, as well as having many applications in industry.

Dissemination and engagement

The project consortium will hold a School on Optical Clocks in September 2018, in Aosta Valley, Italy. The school will be aimed at PhD students, post-docs, young scientists and engineers in the field with a strong focus on training and education. The scope will include tutorials on the latest advances in frequency metrology and atomic frequency standards.

Whilst this project is focussed on the general advancement of knowledge, the consortium is also actively engaged, through partner crossover, in projects to commercialise optical clocks. A new three-year collaboration with university and industrial partners to build a demonstrator compact optical clock, 'opticlock' has recently begun. This is being funded by the German quantum technologies programme (QUTEGA), and will provide a route for uptake and exploitation of the knowledge generated within this project. A commercial product will lead to optical clocks becoming readily available beyond the laboratory to a much wider audience.

Impact on relevant standards

This project is working to verify the performance of optical clocks at the 10^{-18} level in the following atomic clock species: ^{87}Sr, ^{171}Yb, ^{88}Sr^{+}, ^{171}Yb^{+}(E2) and ^{171}Yb^{+}(E3). The results are disseminated to a range of standards and technical committees, including the Consultative Committee for Time and Frequency (CCTF) that makes recommendations on updating values for the secondary representations of the SI second. New optical frequency ratios and absolute frequency values measured during this project [11, 12] will thus lead to smaller uncertainties in the secondary representations of the SI second. The knowledge gathered in this research also greatly informs the international decision about the best choice of atomic clock species for a redefinition of the second.

Impact on industrial and other user communities

Work has begun on bringing together the knowledge generated throughout this project to produce a set of specifications and recommendations for achieving 1×10^{-18} uncertainty optical clocks. The document will be made publicly available and will make it easier for end users to upgrade or build new solutions for their own particular needs. Examples of end users we are targeting that could benefit from low uncertainty optical clocks include radio astronomers needing to synchronise arrays of telescopes in very long baseline interferometry [13], and surveyors needing high spatial and temporal resolution of gravity potentials [14]. With the advent of an optical redefinition of the SI second, there will also be increased demand for local realisations of the new primary frequency standard. Designs and specifications such as produced in this project could greatly facilitate the wider use of optical clocks.

Impact on the metrology and scientific communities

The techniques developed within this project for improved laser stabilities and trap coherence times will be shared to enable optical atomic clocks to be operated with up to an order of magnitude better stability. This will reduce the averaging time needed to reach a given statistical uncertainty by up to two orders of magnitude, making optical clocks far more practical for both ‘in the field’ and laboratory measurements.

For fundamental physics, optical frequency standards at the 1×10^{-18} level can probe for deviations from theoretical predictions with an order of magnitude more precision than currently available. The optical frequency ratio measurements carried out in this project will contribute to the body of data placing limits on the time variation of the fine structure constant. The improved stability of the clocks will also enable more sensitive tests of fundamental physics [15], including dark matter searches [16]. The optical clocks will be an essential part of the ground segments for space-based missions testing General Relativity, such as the Atomic Clock Ensemble in Space (ACES) which is due to be launched in 2019.

Longer-term economic, social and environmental impacts

Precision frequency and timing information is at the core of many technologies upon which society increasingly relies. Examples include satellite navigation, telecommunications and energy networks. Improved atomic clocks can bring significant benefits to the level of these services and stimulate growth in new applications. There is also considerable interest in using optical clocks as sensors of gravity potential to provide increased spatial and temporal resolution for surveying changes at the Earth’s surface. These include monitoring 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.

List of publications

[1] 1.5 µm lasers with sub-10 mHz linewidth
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[3] Dispersive heterodyne probing method for laser frequency stabilization based on spectral hole burning in rare-earth doped crystals
O. Gobron, K. Jung, N. Galland, K. Predehl, R. Le Targat, A. Ferrier, P. Goldner, Seidelin, and Y. Le Coq,
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[5] Phase-noise cancellation in polarisation maintaining fibre links
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[8] On-line estimation of local oscillator noise and optimisation of servo parameters in atomic clocks
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[9] Auto-Balanced Ramsey Spectroscopy
C. Sanner, N. Huntemann, R. Lange, C. Tamm and E. Peik,
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[10] A noise-immune cavity-assisted non-destructive detection for an optical lattice clock in the quantum regime
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[11] Absolute frequency measurement of the $^1S_0 – ^3P_0$ transition of ^{171}Yb
M. Pizzocaro, P. Thoumany, B. Rauf, F. Bregolin, G. Milani, C. Clivati, G. A. Costanzo, F. Levi and D. Calonico,
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