

Title: Controlled confinement to reduce the inaccuracy of clocks based on optical lattices

Abstract

Optical lattice clocks (OLC) have excellent stability and accuracy and are already providing relevant contribution to the realisation of UTC. Their increased reliability also allows them to be used for long distance comparisons, e.g. between Europe, USA, and Japan. OLC have demonstrated uncertainty in the mid to low 10^{-18} , however further investigation of the fundamental limits of their uncertainty and stability is needed. These investigations should include novel configurations for the optical lattice confining the atoms. Further to this, remote clock comparisons, using a variety of different OLC configurations, are needed to demonstrate improved clocks and the accuracy of clock frequency ratios.

Keywords

Optical lattice clocks, accuracy, frequency standards, redefinition of the SI second, clock comparisons

Background to the Metrological Challenges

As the performance of optical frequency standards improves, so their potential applications in fundamental and applied sciences increases. For example, remote comparisons of OLC can be used in tests of fundamental physics (e.g. Lorentz invariance, searches for dark matter) or chronometric geodesy. Recently there has been increased interest in hybrid atom-cavity systems and their application in OLC. Several research milestones have been achieved, including the first demonstration of entanglement-enhanced stability and the first realisation of spin-squeezed clocks, by strongly coupled optical cavities, at a measurement resolution level of 10^{-17} . However, information is currently lacking on the potentially detrimental effects on OLC accuracy by (i) the cavity coupling, (ii) the chosen trapping topology (collinear with the cavity axis or orthogonal), and (iii) by possible optomechanical effects during the entangled state preparation and detection.

Over the past few years, the development of optical frequency standards in NMIs and the associated commercial availability of ultra-stable clock lasers has facilitated the development of fully controllable arrays for OLC. That is OLC in which the quantum states of atoms can be individually controlled, detected, and entangled with high fidelity and extended coherence times. Novel platforms for cold atoms are also currently being developed by academic groups, such as trapping atoms in optical tweezers, loading atoms in hollow core fibres and the design of continuous sources of cold atoms. However, the metrological capabilities of these different trap geometries/compositions in OLC have not yet been fully investigated.

The study of hot collisions in shallow optical traps is a fundamental aspect of the physics of OLC. Traditionally, a semi-classical approach has been used to evaluate the associated systematic frequency shift. However, as this effect limits the accuracy of optical clocks, so more complete, fully quantum, models are needed (together with new experimental data). To be successful these new models also need to take into account the deviation from the semi-classical model and consider the residual gas composition.

OLC currently have an uncertainty in the 1×10^{-18} range. This accuracy is, in some cases, backed by clock comparisons that demonstrated statistical resolutions and agreements between independent clocks. However, the comparison of optical clocks with a wider variety of trapping configurations, environments, and evaluation methods are missing and are urgently needed to increase confidence in clock accuracy and reproducibility.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the

overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of clocks based on optical lattices.

The specific objectives are

1. To study the systematic effects associated with lattice light-shifts and cold collisions by developing tailored dipole trapping potentials for OLC. In addition, to determine how to mitigate lattice-induced de-coherence in shallow lattices, and to mitigate the collision effects that currently limit the use of bosonic isotopes. OLC configurations should include (i) high order transverse Gaussian beams, (ii) patterned or painted potentials, and (iii) Floquet engineered shallow potentials. Sub- 10^{-18} comparisons of lattice light shifts and cold collision shifts (for 10^4 to 10^5 atoms) should be assessed with these configurations.
2. To demonstrate engineered or movable potentials, for dead-time free clocks and active clocks, using novel techniques (e.g. cold atoms in optical tweezers, hollow core fibres, continuous loading of cold atoms, conveyor belt potentials). Then using this ability to control and modify the OLC trap geometry, (i) to explore cold collision effects, and (ii) develop methods for the continuous flux of atoms.
3. To demonstrate fast and low-noise readout of hybrid cavity OLCs in environments where strong light-matter interaction is overlapped with the optical lattice. In addition, to study the effects at fractional resolutions of 10^{-18} or lower, associated with synthetic interactions and entangled states.
4. To determine the effect of background gas collisions with atoms trapped in dipole traps at fractional resolutions of 10^{-18} : This should include the (i) measurement of the atom trapping lifetime and frequency shift using clock comparisons, (ii) the controlled insertion of background gas pressure; and (iii) comparison with theoretical models, i.e. from semi-classical approaches to quantum approaches including the anisotropy of collisions.
5. To demonstrate the improved accuracy of OLCs gained from Objectives 1-4 using agile optical fibre link comparisons between European metrology institutes. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, research organisations (EMN Quantum), standards developing organisations (CIPM Consultative Committee for Time and Frequency (CCTF), EURAMET TC-TF) and end users (time and frequency, fundamental physics and geodesy sectors).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMRP and EMPIR projects EXL01 QESOCAS, 15SIB03 OC18, 17FUN03 USOQS and 18SIB05 ROCIT and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,

- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the time and frequency fundamental physics and geodesy sectors.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.