EMPIR Call 2015 – Health, SI, Normative and Research Potential

Selected Research Topic number: **SRT-s16**
Version: 1.0

Title: Optical clocks with 1E-18 uncertainty

Abstract

Knowledge, methods and techniques for the reliable and efficient evaluation of optical clocks with a total fractional uncertainty in the low 10^{-18} range need to be developed. Optical clocks with laser-cooled ions in radiofrequency traps and neutral atoms in optical lattices exhibit promising performances to achieve this. With improved short-term stability, optimised interrogation schemes and a high duty cycle, fractional systematic effects in the 10^{-18} range should be evaluated precisely within a workable measurement time which should enable the transition from proof-of-principle experiments to applications of the next generation of atomic clocks at an improved level of accuracy.

Keywords

Optical clocks, frequency standards, SI second, trapping and laser-cooling of atoms and ions, laser frequency stabilisation, optical frequency measurement

Background to the Metrological Challenges

In response to the redefinition of the second the development of optical frequency standards based on laser-cooled and trapped atoms and ions has progressed significantly. Currently, two different systems (ions in radiofrequency traps and neutral atoms in optical lattices) have estimated fractional systematic uncertainties in the 10^{-18} range. This progress was made by controlling the frequency shift induced by blackbody radiation, through a combination of high-precision measurements of atomic polarisabilities and control and diagnosis of the thermal environment of the atoms. However, the two different systems for the atomic reference have some challenges to address in common.

It is difficult to quantitatively evaluate, in the 10^{-18} accuracy range, the new generation of optical clock standards and verify the evaluated performance under routine operation. The stability of the frequency standards must be improved into the low 10^{-16} range in 1 s, so that an evaluation with a statistical uncertainty in the low 10^{-18} range can be performed within one day of measurement time which will make the frequency standard practical for more applications. This goal will require improvements in the laser oscillators, the atomic systems (higher atom numbers in the optical lattice, longer interrogation times for the trapped ions) and in the methods to link, distribute and control the radiation from reference lasers. Recently developed passive reference resonators based on single-crystal silicon at cryogenic temperature provide the required low noise level and have been applied in the operation of an optical frequency standard, but the achieved instability is presently degraded from excess noise from the frequency transfer via the frequency comb.

Improved laser stability will also be beneficial for lattice clocks, allowing the quantum projection noise level to be reached for higher atom numbers than currently possible. Optical lattice clocks with neutral atoms have reached instability in the low 10^{-16} range at 1 s, but are subject to larger systematic frequency shifts that need to be controlled precisely. For the dominant shift due to thermal radiation at room temperature, the combination of highly precise measurements of the relevant static and dynamic differential polarisabilities and the stabilisation and precise determination of the thermal field at the position of the atoms has allowed uncertainty estimation in the 10^{-18} range limited by imperfections in the construction of the apparatus. An alternative approach to reducing the shift and the uncertainty is to interrogate the atoms inside a cryogenically cooled enclosure which may also open the pathway to the 10^{-19} uncertainty.

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 must be clearly stated in the protocol.

The JRP shall focus on the development of knowledge, methods, and techniques for the characterisation of optical clocks with a total fractional systematic uncertainty in the 10^{-18} range.

The specific objectives are

1. To develop traps for atoms and ions that enable >1 s coherent interaction times, leading to sub-Hz resonance linewidth with high contrast.
2. To develop reference laser oscillators with mHz linewidth and sub-mHz/s drift rates, enabling interrogation times >1 s and optical frequency standards with fractional instability in the low 10^{-16} range at 1 s and a systematic relative uncertainty of 10^{-18}.
3. To improve the control of the light shift from blackbody radiation for room temperature and cryogenic environments, including measures to improve thermal homogeneity to a few tens of mK and to allow for accurate temperature measurements at this level. To investigate and control higher-order lattice light shifts and collisions in 1D lattices.
4. To develop, implement and test optimised interrogation methods to provide the connection between the reference laser frequency and the atomic reference, ensuring maximally efficient processing of the atomic signal and insensitivity against perturbations that would result in frequency offsets. The objective of the relative clock uncertainty is 10^{-18}.
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers) and end users (space, aerospace, telecommunications and energy networks)

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources outside Europe is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry.

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 project IND14, EMRP project IND55, EMRP project SIB55 and EMRP project EXL01 and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.8 M€, and has defined an upper limit of 2.1 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 21 % of the total EU Contribution to the project. Any deviation from this must be justified.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded 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,
- Transfer knowledge to the metrology, physics and geodesy sector.

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 EMPIR 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.