Title: Optical clocks for the redefinition of the SI second

Abstract

Optical atomic clocks have now reached levels of performance that clearly surpass the stability and accuracy achievable with caesium microwave primary frequency standards and should be brought to the stage where they can contribute regularly to international timescales as secondary representations of the second. However, for this to be possible, significant improvements to the robustness of optical clock hardware are required, as well as monitoring and automated control systems. Furthermore, long-term international consistency of the clocks must be demonstrated through a programme of international comparisons. Tools for automated validation of clock and frequency comparison data should be developed to enable optical clocks to be incorporated into national and international timescales. This is a prerequisite for the second to be redefined in terms of an optical transition frequency.

Keywords

Optical clocks, frequency standards, frequency comparison, timescales, SI second

Background to the Metrological Challenges

An optical redefinition of the second was identified as one of the "Grand challenges on fundamental metrology" within the EMRP Outline in 2008, and was restated as a key target in the 2012 EURAMET roadmaps for time and frequency. As a first step towards such a redefinition, the International Committee for Weights and Measures (CIPM) introduced the concept of secondary representations of the second, and eight optical atomic clocks can now be used in this way. However, as yet, no optical clocks are routinely contributing data to TAI. This issue was recognised by the CCTF in Recommendation CCTF 1 (2017).

So far only one research institute in Europe has contributed optical clock data to the BIPM. Data from their strontium optical lattice clocks (Sr2 and SrB) was included in Circular T on one occasion following approval by the WGPSFS [9], but was not used for steering. Like other optical clocks, these strontium lattice clocks are not yet robust enough to contribute on a routine basis. Although a few simulations have been carried out to investigate the stability improvements that might result from incorporating optical clocks into local physical realisations of UTC, it was only very recently that the first experimental studies have been started. No NMIs are yet using optical clocks as part of their UTC(k) timescales.

Although optical clock uptimes as high as 80% – 90% have been achieved over periods of a few weeks, this required round-the-clock monitoring and a high level of user intervention to recover failures rapidly. Such an approach is unsustainable over longer periods, and if the clocks are left unattended then uptimes are typically far lower, meaning that they cannot routinely contribute to TAI. Caesium fountain primary frequency standards, in contrast, can routinely achieve uptimes greater than 95% with minimal user intervention. In terms of performance, the most advanced optical clocks have reached estimated systematic frequency uncertainties of 2 – 3 parts in 10^{18}, with statistical fractional uncertainties that can average down as rapidly as $6 \times 10^{-17}\ \tau^{-1/2}$.

The only comparison technique so far demonstrated to be capable of comparing clocks at a comparable level of accuracy is transmission of a coherent optical carrier signal over a specially configured optical fibre link. This approach is not yet available to most institutes as it requires a large investment in the necessary fibre infrastructure. The best international clock comparison carried out to date over such a link is a comparison of strontium optical lattice clocks that reached a fractional uncertainty of 5×10^{-17}, limited by the clock uncertainties at the time of the measurement campaign (rather than the link).

There are a range of different optical clock systems currently being studied and the CCTF and CIPM need to make good informed decisions as to the most promising candidates for a redefinition. The only way to determine the level at which it will be possible to redefine the SI second is through extensive and repeated clock comparisons.

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 optical atomic clocks in preparation for the redefinition of the SI second.

The specific objectives are

1. To improve the robustness of optical clocks and automate their operation by achieving unattended uptime of 80 % – 90 % over a few weeks. This should include both trapped ion and neutral atom lattice clocks. Monitoring and automated control systems for both atom and ion clocks should be developed, as well as tools for on-the-fly correction of systematic frequency shifts to prepare the way for real-time steering of local realisations of Coordinated Universal Time (UTC).
2. To investigate the international consistency of optical clocks through a coordinated programme of comparisons. Where possible these comparisons should exploit optical fibre links, in order to achieve the lowest fractional uncertainties $< 10^{-18}$, but GPS-based satellite techniques should also be used. To enable consistency checks in the absence of a direct link between clocks, local optical frequency ratio measurements should be included. Caesium primary frequency standards, which provide traceability to the present definition of the SI second with the lowest possible uncertainty, should be included in the comparisons. Approaches should be studied for handling correlation and averaging of data to efficiently suppress noise without introducing bias.
3. To demonstrate, both by simulation and experimentally, methods for incorporating optical clocks into local realisations of UTC(k). Different algorithms should be tested and compared. Methods should be developed for automated validation of data from the optical clock and the optical frequency comb used to relate the frequency of the optical clock to the frequency of a hydrogen maser that forms part of the local timescale. In addition, robust methods should be developed for automated detection and removal of cycle slips and outliers.
4. To incorporate optical clocks into international timescales as secondary representations of the second. This should be achieved through i) comparison of optical clocks with clocks (e.g. hydrogen masers) that are used in the computation of International Atomic Time (TAI), and ii) submission of this frequency comparison data to BIPM for inclusion in the bulletin Circular T.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the optical metrology community e.g. BIPM CCTF.

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 SIB55 ITOC.

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 20 % of the total EU Contribution across all selected projects in this TP.

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 communities.

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.