European Partnership on Metrology
Call 2025 – Health, Integrated European Metrology, Regulation and Research Potential

Selected Research Topic number: **SRT-s10**
Version: 1.0

Title: Optical clocks for improved time scales

Abstract

Optical clocks outperform their microwave counterparts by about two orders of magnitude. Their far superior realisation of the unperturbed reference transition frequency promises for these systems to be pristine timekeepers. However, to date, optical clocks provide no relevant impact for the users of metrological time services. To benefit from the superior performance of optical clocks, methodologies for the realisation of UTC(k) time scales with optical clocks and corresponding International Atomic Time (TAI) steering are needed. Proposals addressing this topic should develop and validate the required optical reference standards and optical fibre links to meet these needs, including alternative flywheel oscillators to help overcome the existing technological dependence on hydrogen masers.

Keywords

Atomic time scales, optical clocks, time metrology, H-masers ultra-stable oscillators, time services, SI second.

Background to the Metrological Challenges

Time scales provide the fundamental structure for our daily lives and are vital to global communication, digital infrastructure and satellite-based navigation. In addition to the time scales operated by National Metrology Institutes (NMIs) and Designated Institutes (DIs) as part of their legal mandate, time scales are also produced by telecommunication and data service providers, for geodesy and global navigation, and are part of Europe's critical infrastructure.

The technologies used for time scales today process signals in the radio-frequency and microwave range and place particularly high demands on reliable, continuous operation. For the highest metrological requirements, the development of optical frequency standards (OFS) has recently made great progress, with optical atomic clocks claiming accuracy two orders of magnitude better than the best microwave standards. However, the impact of such systems on international time scales and the benefit to users of metrological time services has been negligible. The development of improved time scales also aligns with efforts towards the redefinition of the SI second. Mandatory criteria I.4 of the Consultative Committee for Time and Frequency's (CCTF) roadmap paper [1] requires "regular contributions of optical frequency standards to the international atomic time scale (TAI)" but has only reached a fulfilment level of 30-50 % so far. Realisations of time scales at NMIs/DIs in Europe has heavily relied on the operation of hydrogen masers as flywheel oscillators to provide stable microwave signals and operational robustness. To improve the resilience of Europe's time metrology infrastructure, novel methodologies and flywheel oscillators must be developed.

Europe has a growing competence in quantum technologies, initially stimulated by European and national initiatives on quantum technology and advanced for metrological application in EMPIR and Metrology Partnership projects 15SIB03 OC18, 18SIB05 ROCIT, 18SIB06 TiFOON, 20FUN01 TSCAC, 20FUN08 Nextlasers, 22IEM01 TOCK, 23FUN02 CoCoRICO and 23FUN03 HIOC. This new expertise, also supported by advancements in quantum technology, puts optical time scales within reach. These can be realised using an OFS that steer the output of one or more continuously operating optical flywheel oscillators. However, to avoid time uncertainties from measurement dead time, the robustness of OFS needs to be further advanced, targeting uptimes of the OFS of >90 %. The requirements on the operational robustness of the flywheel oscillators and the time scale synthesis are more demanding still, as continuous operation over months or even years is essential to avoid interruptions that would cause time discontinuity.

As the accuracy of time scales depends primarily on that of the OFS employed for steering, remaining frequency shifts need to be compensated for. Currently, such corrections are applied in post-processing, so methodologies must be developed and validated to enable on-the-fly compensation with low uncertainty. Proper operation of such procedures needs to be validated in comparison with independent optical frequency standards. A direct verification of the intended shift correction can be obtained from frequency comparisons between independent OFS. Here, the targeted performance for the OFS should align with what is achieved for OFS with post-processing, i.e. systematic uncertainties below 2×10^{-18}.

To verify the performance of optical time scales, independent realisations need to be compared via different techniques. Established microwave links for time and frequency transfer, e.g. via Global Navigation Satellite Systems (GNSS) are a straightforward option, allowing for time-interval uncertainties significantly below 1 ns. Lower uncertainties will be supported for international and intercontinental comparisons via Atomic Clock Ensembles in Space (ACES). Even smaller uncertainties could potentially be achieved with optical fibre link time transfer. Here, for links between different NMIs/DIs in Europe an interoperable system for monitoring the operational status of the entire link needs to be established to facilitate their application for continuous comparisons of the independent time scales.

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 proposal shall focus on the development of novel methodologies for the realisation of UTC(k) time scales with optical clocks.

The specific objectives are

1. To develop continuously operating optical flywheel oscillators and corresponding methodologies for their steering with optical clocks that enable UTC(k) time scales with below 1 ns time instability for extended periods of time and typically longer than 30 days.
2. To strengthen the unattended continuous operation of optical clocks and optical time scale synthesis, aiming for: i) optical clock uptimes of ≥90 % ii) continuous operation of the time scale and iii) development and validation of optimal steering algorithms of the flywheel oscillator over 30-day measurement intervals.
3. To develop and validate methodologies for on-the-fly frequency shift control of optical clocks employed for the steering of local time scales with systematic uncertainties below 2×10^{-18}.
4. To compare and validate UTC(k) time scales employing optical clocks via optical fibre links. To improve the availability and enhance access for NMIs/DIs to time transfer links with below 1 ns uncertainty.
5. To demonstrate the establishment of an integrated European metrology infrastructure for optical time scale generation and comparison and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs), the international metrology community (e.g., CIPM CCTF, CGPM) and end users (industry, the broader research community).

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 both within and outside Europe, plus engagement with existing European research infrastructures and European Partnerships 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 and end users. Where relevant, proposals are encouraged to build on, or seek collaboration with, existing projects and develop synergies with other relevant European, national or regional initiatives and funding programmes. In particular, links are encouraged with (i) the projects funded under earlier relevant topics of the Horizon Europe programme; or (ii) other relevant European Partnerships.

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 EMPIR projects 15SIB03 OC18, 18SIB05 ROCIT, 18SIB06 TiFOON, 20FUN01 TSCAC and 20FUN08 Nextlasers, and Metrology Partnership projects 22IEM01 TOCK, 23FUN02 CoCoRICO and 23FUN03 HIOC and how their proposal will build on those.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.1 M€ and has defined an upper limit of 2.6 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 25 % 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 proposal's 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 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 the Metrology 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.

Timescale

The project should be of up to 3 years duration.

Additional information

The links provided in this section are only correct at the time of publication up until the end of the Call year.

The references below were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] Roadmap towards the redefinition of the second
https://iopscience.iop.org/article/10.1088/1681-7575/ad17d2