# Publishable Summary for 20FUN01 TSCAC

**Two-species composite atomic clocks**

**Overview**

Highly accurate and stable frequency standards are essential for telecommunications, and satellite navigation. Optical clocks that utilise fundamental atomic properties are set to become the future primary measurements standards for time and frequency replacing the caesium clocks in use today. Composite atomic clocks based on multi-species atoms have the potential to introduce even greater accuracy, stability, and reliability than existing single atom clocks. This project will investigate two-species composite atomic clocks based on established atomic clock species and explore new reference transitions in highly charged ions that promise to further improve the performance of clock systems.

**Need**

The fundamental properties of atoms provide characteristic microwave or optical frequency references used in atomic clocks to realise the most precise measurement devices available today. Within the SI system of units, the realisation of the unit of time with Caesium atomic clocks plays an essential role, as the unit second is contained in the definition of 6 of the 7 base units via the defining constants. Having highly accurate, stable, and reliable reference frequency standards is a pre-requisite not only for the SI System of Units, but also for many everyday technologies that rely on precise time keeping such as banking transactions, communication, and navigation.

Resulting from the higher reference transition frequency, highly precise optical clocks have made great progress with a variety of different reference systems with neutral atoms and single ions. The seminal proposals and much of the experimental work to date have been focused on atomic clocks based on single reference transitions. The combination of advantages of established reference systems in two-species composite atomic clocks promises to achieve even better performance as required by the growing needs in communication and navigation.

The first realisations of these promising composite clocks, with single systems even at distant locations, require the development of the necessary measurement infrastructure and related methodologies such as interrogation protocols and corresponding data processing (Obj. 1). To compare such highly accurate clocks in measurement campaigns shorter than weeks, their frequency instability needs to be improved. This can be achieved by utilising clocks based on many atomic absorbers (Obj. 2). The realisation of unperturbed transition frequencies as standards for time and frequency requires knowledge of the size of frequency shifts caused by residual perturbing fields at the position of the reference atoms. Sensitive atomic transitions of the same atom or ancillary atoms can provide the means to calibrate residual fields and enable precise corrections to improve clock accuracy (Obj. 3). Alongside the use of established atomic reference transitions, novel systems with greater immunity to the electric or magnetic fields inherent in atomic clock operation are of particular interest. These novel systems include a low-energy nuclear transition in 229Th and transitions in highly charged ions (HCI), but currently their atomic transition frequencies are not known to the required accuracy. Additionally, theoretically predicted characteristics need to be experimentally investigated (Obj. 4). To enable specialised research laboratories to search for and perform initial spectroscopy on yet to be discovered clock transitions, frequency references with increased reliability are needed (Obj. 5).

**Objectives**

The overall objective of the project is to perform metrology research necessary to support the use of multi‑species composite atomic clocks as future SI standards.

The specific objectives of the project are:

1. To develop and optimise the interrogation sequences, signal links and real-time data processing and cooling methods that enable composite clocks or different clock types to stabilise one common oscillator, to obtain a stability and accuracy that would not be achievable with the use of each clock system separately. This includes the application to systems that are distributed over two or more different locations.
2. To reduce the frequency instability of optical clocks with single or few atoms/ions of typically above 1 × 10-15/(s) and the correspondingly long averaging times due to quantum projection noise to below 1 × 10-15/(s) using information obtained in simultaneous measurements performed on ensembles of many atomic absorbers.
3. To improve the frequency accuracy in single-species atomic clocks by using established reference transitions in two-species optical clocks or with atoms possessing two reference transitions using precisely measured relative sensitivities to external fields.
4. To investigate new reference transitions in two-species composite systems, to enable clock operation and absolute frequency measurements for transitions in so far inaccessible atomic systems (such as highly charged ions) with target uncertainties at the 1 Hz level. This is equivalent to a relative uncertainty of 2 x 10-15. This includes the direct investigation of theoretically predicted characteristics of these transitions and associated systematic shifts via a readout scheme using an ancillary ion.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, research laboratories), and possible end users (space, aerospace, telecommunications, energy).

**Progress beyond the state of the art**

This project (TSCAC) builds upon the achievements of previous EMRP and EMPIR projects, most recently 17FUN07 CC4C and 18SIB05 ROCIT. While fundamental techniques such as trapping and cooling of ions of different species simultaneously for clock application have been investigated in CC4C, TSCAC will demonstrate the first clocks making use of the potential benefit of the co-trapped species in clock operation. Due to the potentially higher accuracy and improved stability achievable within TSCAC, fundamental metrology research on composite systems of established optical clocks and new reference transitions will be performed to support the use of multi-species composite atomic clocks as future SI standards.

*Novel methodologies for composite systems*

The use of multi-species atomic clocks opens new perspectives in terms of accuracy and stability for optical clocks. The first demonstration of an optical atomic clock that uses different atomic species has been the Al+ ion clock that requires an ancillary ion for interrogation. Today, an advanced version of this clock is the first among all atomic clocks reporting a fractional frequency uncertainty slightly below 10-18. New interrogation methods that provide immunity to frequency shift effects in different combinations of atomic species or automatically correct for those measured in interleaved interrogations on ancillary atoms will be developed by this project. These methods include cooling of the ion by contact to a laser-cooled auxiliary ion (sympathetic cooling) that permit very long coherent laser atom interaction times and thus shorter averaging times. Signal links and real-time data processing will be set up to interconnect atomic clocks of different kinds to obtain a stability and accuracy that would not be achievable with the use of each clock system separately.

*Composite clocks for improved stability*

Higher clock stabilities are needed, to keep the averaging times required to realise the further reduced fractional clock uncertainties of a few 10-19 at an acceptable level of a few days. Several proposals to circumvent or reduce limiting laser noise by interrogation of more than one optical clock exist and have been successfully demonstrated in some configurations. This project will systematically investigate the most promising approaches of local-oscillator pre-stabilisation, and interrogation longer than the laser coherence time, apply them to state-of-the-art optical clocks and compare their benefits in order to reduce averaging times of optical clocks.

*Improved accuracy enabled by two species or two transitions*

Optical clock systems utilising two atomic species in the same trap or multiple transitions within the same atom or ion can be exploited to improve the overall accuracy of the clock by investigating and quantifying systematic frequency shifts using novel interrogation methods. In a variety of atom and ion trapping systems this project will examine the most relevant systematic frequency shifts in depth e.g. those due to atomic motion and exposure to DC and AC magnetic and electric fields and blackbody radiation, through modelling and by experimental observation to enable systematic uncertainties in the 10-19 level, enabling increased sensitivity in many applications (e.g. geodesy and fundamental physics) well aligned with the accuracy target required by the CCTF roadmap to redefine the SI second. Utilising transitions in ancillary atoms and ions, as well as by way of exciting different transitions within the same ion will allow us to perform real-time calibrate perturbing fields and apply correction of dynamic changes in systematic effects during optical clock operation.

*New reference transitions and quantum logic in mixed-species systems*

Measurements of optical transitions in highly charged ions (HCI) will be demonstrated that are more than a million times more accurate than the present state of the art, which lies at a fractional uncertainty of 9 x 10‑9, and will bring highly charged ions into the accuracy realm of optical atomic clocks. Also, the first direct XUV laser spectroscopy of an electronic transition in a cold HCI will be performed, establishing a new super-optical frequency range for precision spectroscopy in trapped ions. In parallel, the establishment of the frequency measurement architecture for the 229Th nuclear transition will be pursued, including the development of a VUV frequency comb and its reference to the composite clock network. This transition has never been directly driven with lasers and possesses the potential to revolutionise ion-based optical atomic clocks, yielding a frequency standard that promises exceptional clock performance with levels of stability and accuracy that surpass the best optical frequency standards operating today.

**Results**

*Objective 1: Novel methodologies for composite systems*

New interrogation methods that provide immunity to frequency shift effects in different combinations of atomic species or automatically correct for those measured in interleaved interrogations on ancillary atoms are currently being developed by this project. These methods include cooling of the ion via Coulomb interaction with laser-cooled auxiliary ion (sympathetic cooling) that permit very long coherent laser atom interaction times and thus shorter averaging times. Signal links and real-time data processing are set up to interconnect atomic clocks of different kinds to obtain a stability and accuracy that would not be achievable with the use of each clock system separately. A publication on the characterisation of a fibre link connecting distributed clocks has been published.

*Objective 2: Composite clocks for improved stability*

Higher clock stabilities are needed, to keep the averaging times required to realise the further reduced fractional clock uncertainties of a few 10-19 at an acceptable level of a few days. Several proposals to circumvent or reduce limiting laser noise by interrogation of more than one optical clock exist and have been successfully demonstrated in some configurations. Within this project, the partners systematically investigate the most promising approaches of local-oscillator pre-stabilisation, and interrogation longer than the laser coherence time, apply them to state-of-the-art optical clocks and compare their benefits in order to reduce averaging times of optical clocks. In initial tests, a coherent interrogation of up to 2 s has been observed with a single ion optical clock. This result was essentially limited by the noise of the local oscillator. Consequently, further improvements are to be expected.

*Objective 3: Improved accuracy enabled by two species or two transitions*

Optical clock systems utilising two atomic species in the same trap or multiple transitions within the same atom or ion can be exploited to improve the overall accuracy of the clock by investigating and quantifying systematic frequency shifts using novel interrogation methods. In a variety of atom and ion trapping systems this project will examine the most relevant systematic frequency shifts in depth e.g. those due to atomic motion and exposure to DC and AC magnetic and electric fields and blackbody radiation, through modelling and by experimental observation to enable systematic uncertainties in the 10-19 level. The increased sensitivity permits application of these clocks in related research fields such as fundamental physics and is well aligned with the accuracy target required by the CCTF roadmap to redefine the SI second. Utilising transitions in ancillary atoms and ions, as well as by way of exciting different transitions within the same ion will allow us to perform real-time calibrate perturbing fields and apply correction of dynamic changes in systematic effects during optical clock operation. So far microwave spectroscopy has been set up for single ions and is now enabling detailed study of tensorial frequency shifts. Furthermore, using Sr+ as an ancillary ion has permitted two partners to perform a precision measurement of AC magnetic fields.

*Objective 4: New reference transitions and quantum logic in mixed-species systems*

Measurements of optical transitions in highly charged ions (HCI) have been demonstrated that are more than a million times more accurate than the previous state of the art, which laid at a fractional uncertainty of 9 x 10‑9. The realisation of an optical clock based on a highly charged ion brought these systems into the accuracy realm of optical atomic clocks. Furthermore, the first direct XUV laser spectroscopy of an electronic transition in a cold HCI will be performed, establishing a new super-optical frequency range for precision spectroscopy in trapped ions. In parallel, the establishment of the frequency measurement architecture for the 229Th nuclear transition is pursued, including the development of a VUV frequency comb and its reference to the composite clock network. This transition has never been directly driven with lasers and possesses the potential to revolutionise ion-based optical atomic clocks, yielding a frequency standard that promises exceptional clock performance with levels of stability and accuracy that surpass the best optical frequency standards operating today. Since the beginning of the project, a major part of the fibre optical link of the composite clock network has been established and characterisation has begun.

**Impact**

The impact of this work is predominantly on the scientific community and on the long-term development of metrological capabilities at the frontiers of measurement science. Longer-term economic impact from knowledge transfer to industry is foreseeable.

After start of the project a website has been set up to inform about this project and it has been updated frequently. The significant impact on scientific communities is well indicated by 5 published papers and 31 conference presentations from partners of the project within the first 18 months, including invited talks at the Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), the European Conference on Trapped Ions 2021 and the Virtual Atomic, Molecular and Optical Physics Seminar (VAMOS). A training course on “Optical atomic clocks: basic principles and applications” at the WACQT Summer School 2021 provided ideas to more than 50 participants. A much larger audience has been reached by an online video presentation on YouTube with contributions from project partners has presently more than 150,000 views.

*Impact on industrial and other user communities*

Optical clocks are attracting much interest in different sectors, such as space, aerospace, telecommunications, and energy networks because of their superior performance compared with established microwave clocks. Key subsystems of optical clocks (e.g. laser systems, reference resonators, frequency combs, ion traps and optical traps) are already commercially available from several vendors. First demonstrators of future commercial clocks, for application beyond fundamental research, are developed directly by or with strong participation of industrial partners within various projects supported by quantum technology initiatives. Sub‑components of these demonstrators extend to other applications such as precision spectroscopy and quantum information processing. Several project partners have strong links with European and national programmes that aim to develop optical clocks for applications beyond fundamental research. This project will strengthen and widen the relations between NMIs, academic institutes and industry through knowledge exchange and cooperation. For instance, an external collaborator will apply the methodologies on composite clocks developed in the project to the case of transportable clocks or future industrial clocks that do not use highest grade lasers. Moreover, industrial development of optical and electronic systems is supported by the participating NMIs via guidance on target specifications for novel applications and ad-hoc support in the characterisation of commercial prototypes. Here, the activities within TSCAC will be complemented by the Austrian “AQUclock” project, which will provide an optical atomic clock to the established distributed clock network.

*Impact on the metrology and scientific communities*

This project will improve the level of uncertainty realisable with optical atomic clocks by enabling systems that combine advantages of clocks based on transitions in different species. This will improve the stability achievable with single or few-atom systems and reduce the averaging time required to obtain a targeted statistical uncertainty. Techniques investigated will permit application of new reference systems, including a nuclear transition, that are promising candidates for optical clocks. This will provide input to the selection of suitable reference systems for a redefinition of the SI second, an essential contribution to fundamental metrology and to the long-term development of the SI system of units.

This project will foster new interdisciplinary links, and lead to an exchange of technology and know-how between high-precision optical frequency metrology and nuclear physics. High precision methods for optical frequency standards that have been developed by NMIs will be made available to a wider class of systems of scientific interest, such as highly charged ions. This will contribute to an improved understanding of the structure of atoms, molecules, and nuclei, and to tests of fundamental physics through precision spectroscopic studies and frequency measurements on selected systems of high sensitivity (e.g. for violations of Einstein’s equivalence principle).

This project will develop and strengthen the high-level metrological infrastructure in the measurement of time and frequency, and in the longer term it will improve the capabilities in time scale generation and time dissemination. The consortium will liaise with the time section of BIPM, and will report to the Consultative Committee for Time and Frequency (CCTF), to the Consultative Committee for Length - Consultative Committee for Time and Frequency (CCL-CCTF) Working Group on Frequency Standards (WGPSFS) and to the EURAMET Technical Committee for Time and Frequency (TC-TF). In addition, the results will be reported to the European Metrology Network for Quantum Technologies (EMN-Q), in particular to the section on quantum clocks and atomic sensors, and feedback will be collected.

*Impact on relevant standards*

The research in this project is fundamental in nature. As such, no standards are possible at present, however relevant quantum standards development organisations will be sought out and informed of project progress as technologies mature over the project’s lifetime.

*Longer-term economic, social and environmental impacts*

Long-term impact of this research will result from the pivotal role of atomic clocks in the revised SI and in several growing technology sectors. The results will allow the international metrological community to make better informed decisions towards a future redefinition of the SI second. Improved atomic clocks have relevance for technological applications, in sectors such as navigation, space, aerospace, telecommunications and energy networks. Trapped ion optical frequency standards offer excellent accuracy and have the best potential for miniaturisation of the “physics package” (i.e. ion trap, vacuum systems, and optical setup for cooling and detection) and the cooling lasers which is of major importance in their development as payloads on board satellites and aerospace vehicles. Improved optical clocks also allow for geodesy with cm-level precision and applications in geodynamic and climate research.

**List of Publications:**

T. Lindvall, K. J. Hanhijärvi, T. Fordell, and A. E. Wallin, “High-accuracy determination of Paul-trap stability parameters for electric-quadrupole-shift prediction”, J. Appl. Phys. 132, 124401 (2022).

M. Cizek, L. Pravdova, T. Minh Pham, A. Lesundak, J. Hrabina, J. Lazar, T. Pronebner, E. Aeikens, J. Premper, O. Havlis, R. Velc, V. Smotlacha, L. Altmannova, T. Schumm, J. Vojtech, A. Niessner, and O. Cip, “Coherent fibre link for synchronization of delocalized atomic clocks”, Optics Express 30, 5450 (2022).

E. Seres, J. Seres, and T. Schumm,” Group delay dispersion tuned femtosecond Kerr-lens mode-locked Ti:sapphire laser”, Optics Continuum 1, 860 (2022).

A. Linek, P. Morzyński, and M. Witkowski, “Absolute frequency measurement of the 6*s*21*S*0 → 6*s*6*p*3*P*1 *F* = 3/2 → *F*′ = 5/2 201Hg transition with background-free saturation spectroscopy”, Optics Express 30, 44103 (2022).

S. A. King, L. J. Spieß, P. Micke, A. Wilzewski, T. Leopold, E. Benkler, R. Lange, N. Huntemann, A. Surzhykov, V. A. Yerokhin, J. R. Crespo López-Urrutia, P. O. Schmidt “An optical atomic clock based on a highly charged ion” Nature 611, 43 (2022). arXiv:2205.13053

This list is also available here: [https://www.euramet.org/repository/research-publications-repository-link/](http://?)

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| Project start date and duration: | | 1st May 2021 (36 months) | |
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| Internal Funded Partners:   1. PTB, Germany 2. BEV-PTP, Austria 3. INRIM, Italy 4. NPL, United Kingdom 5. VTT, Finland | External Funded Partners:   1. CNR, Italy 2. ISI, Czechia 3. LUH, Germany 4. MPG, Germany 5. TU Wien, Austria 6. UMK, Poland | | Unfunded Partners: |
| RMG: - | | | |