Publishable Summary for 18SIB05 ROCIT
Robust Optical Clocks for International Timescales

Overview

Optical atomic clocks have now reached levels of performance that clearly surpass the stability and accuracy achievable with caesium microwave primary frequency standards, with the result that a future optical redefinition of the SI second is anticipated. This project tackled key steps that must be taken prior to the redefinition. The robustness of optical clocks was improved so that they could run unattended for long periods, methods were developed for automatic data validation enabling prototype demonstrations of optically steered timescales, and the long-term reliability and reproducibility of the clocks were assessed through a coordinated programme of international comparisons. By the end of the project several European optical clocks were contributing on a regular basis to International Atomic Time (TAI) as secondary representations of the second, improving its stability and accuracy. These steps represent important progress towards the criteria set out in the international roadmap towards a redefinition of the second, and since international timescales underpin modern-day technology such as telecommunications and navigation systems, the work will benefit end users across a wide range of sectors in the longer term.

Need

International timescales underpin technology we all depend on, such as modern telecommunications and navigation systems. As these systems continue to evolve, the demands on the stability and accuracy of the reference timescales increases.

At the time this project was proposed, optical atomic clocks had overtaken caesium primary frequency standards, both in terms of fractional frequency instability and estimated systematic uncertainty. A future redefinition of the second was anticipated, and ten optical transition frequencies had been accepted as secondary representations of the second. However, no optical clock had contributed either to the computation of TAI or to the UTC(*k*) timescales maintained by national timing laboratories.

For routine contributions to timescales, significant improvements were necessary to improve the robustness of the optical clocks, so that high uptimes could be achieved without round-the-clock monitoring and frequent user intervention to recover failures. Tools for on-the-fly correction of systematic frequency shifts and automated validation of data were also required to provide data with sufficiently low latency.

Extensive and repeated frequency comparisons between independently developed optical clocks were needed to assess their long-term reliability and reproducibility, and to provide crucial information for the international metrology community, informing their discussions regarding the best candidate for the redefinition. Traceability to the present definition of the SI second was also critical, requiring regular comparisons between optical clocks and caesium primary frequency standards.

These steps were essential prerequisites for the redefinition of the SI second, as clearly expressed by the Consultative Committee for Time and Frequency (CCTF) in Recommendation CCTF 1 (2017) and in their international roadmap for a redefinition of the second. Tackling these challenges required a collaborative approach, since the realisation of international timescales is a global endeavour.

Objectives

The overall objective of this project was to bring European optical clocks to the stage where they regularly contribute to TAI via reporting to the International Bureau of Weights and Measures (BIPM). Specifically, the objectives were:

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

1. To improve the robustness of optical clocks and automate their operation, including tools for on-the-fly evaluation of systematic frequency shifts. The target was to achieve unattended uptimes of 80 % – 90 % over a few weeks for both trapped ion and neutral atom lattice clocks.

2. To investigate the international consistency of optical clocks through a coordinated programme of frequency comparisons. This programme included remote comparisons using both optical fibre links and GPS-based satellite techniques, providing for wide participation as well as the lowest possible fractional comparison uncertainties (below 10^{-18}). Optical frequency ratio measurements enabled consistency checks to be performed where no direct link between clocks existed. Traceability to the present definition of the SI second was provided by absolute frequency measurements relative to caesium primary frequency standards.

3. To demonstrate, both by simulation and experimentally, methods for incorporating optical clocks into local realisations of Coordinated Universal Time (UTC), i.e. the UTC(*k*) timescales maintained by national timing laboratories. Different algorithms were tested and compared, along with methods for automated validation of the optical clock data.

4. To incorporate optical clocks into international timescales as secondary representations of the second, via the submission of data to the BIPM.

5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the optical metrology community, in close co-operation with the CCTF and its associated working groups.

Progress beyond the state of the art

This project built upon the achievements of previous EMRP and EMPIR projects, most recently SIB55 ITOC, 15SIB03 OC18 and15SIB05 OFTEN, to bring several optical atomic clocks to the stage where they were able to contribute regularly to TAI – a significant milestone on the path to the redefinition of the SI second.

Unattended uptimes of 80 % – 90 % over several weeks were achieved for both trapped ion and neutral atom lattice clocks. Prior to the start of the project, such high uptimes had only been achieved with round-the-clock monitoring and frequent user intervention, which is unsustainable over the long periods required for optical clocks to make routine contributions to timescales.

The international consistency of optical clocks was checked through a coordinated programme of frequency comparisons, using both optical fibre links and satellite links. An extended European optical fibre network was shown to the capable of supporting comparisons with long-term fractional instability and accuracy below 10^{-18}. Comparison uncertainties for the most advanced optical clocks were reduced by an order of magnitude or more compared to the state-of-the-art at the start of the project, with the most accurate local frequency ratio measurement reaching a fractional uncertainty of 4×10^{-18}.

Experimental prototypes of UTC(*k*) timescales incorporating optical clocks were demonstrated, building on preliminary paper studies performed within the SIB55 ITOC project. At the start of the project, no laboratories were using optical clocks as part of their UTC(*k*) timescales, and the first experimental studies in this direction had only recently been started in Japan and the USA.

Up-to-date evaluations of the expanding worldwide body of clock comparison data were performed, using methods developed within the SIB55 ITOC project, to check the internal consistency of the data and derive optimal values for the frequencies and uncertainties of optical secondary representations of the second. These are required for TAI steering by optical clocks. Compared to the state-of-the-art at the start of the project, lower uncertainties of the optimal frequency values were obtained, and correlations were taken into account for the first time to ensure that the values are unbiased.

It was only a few months prior to the start of the project that the first optical clock was used for TAI steering, and at that time submission of data was sporadic and had a high latency. By the end of the project, the frequency of data submissions from European optical clocks to the BIPM had increased significantly, and it was being submitted with low latency. The situation will improve further in the coming months as data collected from other clocks within the project is submitted for approval by the CCTF Working Group on Primary and Secondary Frequency Standards (WGPSFS).

Results

Robustness of optical clocks

The robustness of optical clocks was improved by developing new approaches for automatic long-term control of laser systems and for automated adjustment of optical setups. Both trapped ion optical clocks and neutral atom optical lattice clocks were addressed. The focus was on the systems that had been observed to require most frequent user intervention, and a variety of approaches were tested by different partners within the consortium to compare their effectiveness. Methods were developed for automatically relocking lasers to external stabilisation cavities, external enhancement cavities used for second-harmonic generation and enhancement cavities for optical lattices. Systems were also developed for automatic laser beam re-alignment into optical fibres and of objectives for ion imaging. These systems were used by three partners to demonstrate unattended operation of their optical clocks with high uptime, exceeding 80 % over 2 weeks for at least one optical clock in each laboratory. In all cases, a few longer periods of downtime caused most of the downtime. The reasons for these and possible further engineering improvements were compiled.

Software to schedule and perform operational checks, for example the measurement of environmental parameters necessary to correct for systematic frequency shifts, was developed and tested. Experimental control systems were also extended to enable interleaved measurements to be performed to determine the magnitude of residual frequency shifting parameters. These developments enabled three partners to demonstrate on-the-fly evaluation and correction of frequency shifts in at least one of their optical clocks, preparing the way for real-time steering of UTC(*k*) timescales and contributions to TAI.

The objective of achieving unattended uptimes of 80 % – 90 % over a few weeks was achieved for at least one optical clock in each of three laboratories, and these clocks included both trapped ion and neutral atom lattice clocks. The improvements to robustness and automation included tools for on-the-fly evaluation of systematic frequency shifts.

International consistency of optical clocks

A new optical fibre link has been set up from Paris to Turin, to extend the reach of the European optical clock network. This has demonstrated robust performance with long-term fractional instability and accuracy below the 10^{-18} level (limited by the out-of-loop validation). This extension to the European infrastructure means that optical clocks in four different European laboratories (INRIM, NPL, OBSPARIS and PTB) can now be compared at a level commensurate with the performance of state-of-the-art optical clocks.

Two coordinated programmes of frequency comparisons were carried out, in which optical clocks were compared via optical fibre link and satellite-based techniques. The most recent campaign, in March 2022, was the most extensive to date – it involved eleven optical clocks in seven different countries, including two new clocks ($^{88}\mathrm{Sr}^+$ at VTT and $^{115}\mathrm{In}^+$ at LUH) as well as one from outside Europe (the Yb lattice clock at our collaborator NMIJ in Japan). These remote comparisons were supplemented by a number of local optical frequency comparisons, including the measurement of several optical frequency ratios that had never been determined directly before. This collection of measurements greatly augmented the body of high-accuracy clock comparison data available worldwide, with uncertainties being reduced by up to an order of magnitude in some cases. Traceability to the present definition of the second was ensured by including caesium primary frequency standards in the comparison programme.

Importantly, correlation coefficients between the various frequency ratios measured were computed, using guidelines prepared in the early stages of the project. Proper quantification of these correlation coefficients is essential to avoid biasing the recommended frequency values for secondary representations of the second and underestimating their uncertainty.

The objective of investigating the international consistency of optical clocks through a coordinated programme of frequency comparisons has therefore been met.

Optical clocks in UTC(k) timescales

Algorithms and software for real-time validation of data provided by optical clocks were developed, tested and optimised in order to prepare the way for steering of experimental prototype UTCx(*k*) timescales. In this work the whole metrological connection between the atomic reference and the flywheel used to generate the timescale was considered, including frequency combs and local frequency links as well as the optical clocks themselves. Several approaches were developed to detect cycle slips or other anomalous behaviour in the links between the atomic reference and the flywheel, and their effectiveness compared by processing of real measurement data. Algorithms based on moving averages of trapped atom / ion number and transition probability were developed to assess the status of optical clocks, as well as techniques to handle sudden variations of magnetic field.

Two independent steering algorithms were developed for steering a local flywheel with optical clock data. The first addressed the effect of gaps in the optical clock data acquisition and is adapted to low uptimes and long periods of unavailability, while the second was designed to adapt to possible lags between data acquisition and correction, as well as to unexpected changes of the frequency drift of the flywheel. These algorithms were tested and optimised using simulated and historical optical clock data, to guide the subsequent experimental work.

Three partners independently and simultaneously demonstrated prototype optically steered timescales, based on data from one or more optical clocks. For the two laboratories that achieved high optical clock uptimes, the resulting UTCx(*k*) timescales remained less than 2 ns away from UTC over 30 days, despite a few data validation issues and technical issues associated with the frequency offset generators used for steering. These two UTCx(*k*) timescales were also compared directly, the first time such a measurement had been carried out, with their offset remaining smaller than the offset between the corresponding operational UTC(*k*) timescales over the same period.

The objective of demonstrating, both by simulation and experimentally, methods for incorporating optical clocks into the UTC(*k*) timescales maintained by national timing laboratories was thus successfully achieved.

Optical clock contributions to TAI

Two evaluations of the expanding body of clock comparison data available worldwide have been performed, to check its internal consistency and to derive optimal values for the frequencies and uncertainties of secondary representations of the second, which are required for TAI steering by optical clocks. As part of this work, two independent software codes were written to provide independent verification of results generated using software previously developed within the SIB55 ITOC project. The first evaluation was based on all available optical frequency ratio and absolute frequency measurement results from both the consortium and the wider community and differed from earlier work in that detailed consideration was given to correlations between the individual frequency measurements to ensure that the frequency values derived are unbiased and that their uncertainties are not underestimated. Our demonstration that correlations were significant persuaded the CCL-CCTF Frequency Standards Working Group (WGFS) to include them for the first time in the 2021 update to the list of recommended frequency values, a major step forward compared to previous adjustments. The second evaluation included all local and remote frequency ratios measured within the project and resulted in improved uncertainties and in significant changes in the values of the adjusted frequencies for $^{88}\mathrm{Sr}^+$ and $^{115}\mathrm{In}^+$. However, the extended input data set does show some inconsistencies that will need to be addressed ahead of the next WGFS adjustment expected in 2024 – 2025.

Guidelines on the submission of optical clock data to the BIPM were prepared for consortium use. INRIM submitted data from their Yb optical lattice clock, collected prior to the project start, to the BIPM. Following approval from the WGPSFS, this data appeared in BIPM bulletin Circular T no. 383 (November 2019) and was used for TAI steering. Since then, 14 further submissions of optical clock data have been made to the BIPM, five from one of the OBSPARIS Sr lattice clocks, and nine from the INRIM Yb lattice clock. All data was submitted with low latency (before the 4th day of the following month) and was used for TAI steering. This result, together with the submission of optical clocks from outside the consortium and the new recommended values of the secondary representations of the second, resulted in a significant increase in the weight of optical clocks in TAI. NPL submitted data from their Sr optical lattice clock NPL-Sr1 to the BIPM shortly after the end of the project, and this standard is pending approval by the WGPSFS. Four other optical clocks that still require approval by the WGPSFS have been operated and collected large amounts of data with high uptime, which they will be able to use in their first submissions to the BIPM.

The objective of incorporating optical clocks into international timescales as secondary representations of the second, via the submission of data to the BIPM, was achieved, with the target number of submissions being met. However, these submissions came from fewer laboratories and clocks than originally anticipated, as submissions by some laboratories have been delayed, e.g. due to the need for peer-reviewed publications describing improved systematic uncertainties to be available prior to submission.

Impact

The potential uptake of the project results by end users has been promoted by a range of dissemination activities such as presentations at conferences and workshops, and input to metrology committees. The project website presents an overview of the project, together with new updates and announcements, and also provides access to papers, reports and open data produced during the project. Fifteen peer-reviewed papers and two master’s theses have been published. A list of stakeholders has been drawn up and formal collaboration agreements have been put in place with AIST/NMIJ and with the EMPIR 18SIB06 TiFOON consortium. One new optical clock from within the consortium has undergone evaluation by the WGPSFS, and there was extensive interaction with the CCTF and its working groups in the period leading up to the CCTF meeting held in October 2020. Training activities have included two talks at the “Autumn School on Clocks, Cavities and Fundamental Physics” and an invited tutorial lecture at PTTI 2020, as well as several seminars. A final two-day international workshop, held online to disseminate and discuss the results and findings from the project, was attended by more than 200 participants from around the globe.

Impact on industrial and other user communities

The hardware and software developed to improve the robustness and automation of laboratory optical clocks will benefit research groups and industrial organisations developing compact and portable optical clocks for field applications. Several project partners have strong links with European and national programmes that aim to develop such clocks for applications including geodetic height measurements, synchronisation of telecommunications networks and future satellite navigation systems. Trialling approaches on state-of-the-art laboratory clocks will speed up these efforts to commercialise optical clock technology, and some of the software developed has been made available to interested parties on GitHub following an open-source approach. Applications of clock subsystems also extend to other areas such as precision spectroscopy and quantum information processing. Automatic laser re-locking software is being used by at least one university outside the consortium, and knowledge gained within the project has been used to advise industrial organisations participating in ESA’s Technology Research Programme.

Impact on the metrology and scientific communities

The most direct impact of this project is on the future realisation and dissemination of the SI unit of time.

Key outputs from the project are improved frequency values for secondary representations of the second and detailed information about the consistency of optical clocks within Europe. In this way the work has helped to build confidence that the new generation of optical clocks perform at the level expected according to the uncertainty evaluations for individual clocks. It will also help the international community to identify the most promising candidates for a future redefinition of the second.

The measurements and analysis have made significant contributions to improved recommended frequency values for secondary representations of the second, which are now at the limit set by the uncertainties of caesium fountain primary standards. The improvements in the robustness and automation of optical clocks will enable them to be operated regularly as secondary representations of the second, being used to steer local UTC(*k*) timescales and broadening the base of high accuracy clocks available for TAI steering.

These advances are giving European time and frequency metrology institutes a highly influential role within international discussions regarding the future of TAI and the anticipated redefinition of the second.

The work performed will also have spin-off benefits to fundamental physics. For example, comparisons between optical clocks with verified uncertainties can be used to set limits on possible present-day variation in fundamental physical constants, to test the predictions of special and general relativity and to set experimental constraints on dark matter detection. Some of the measurements performed in the project have already been exploited in this way.

Impact on relevant standards

Since the project addressed a future change in the definition and realisation of the SI unit of time, the route to impact was through the CCTF and its working groups. The consortium is well represented on these bodies, where information on the project progress and outputs was disseminated through tailored presentations and written reports.

Contributions to the Frequency Standards Working Group (WGFS) include improved measurements of optical frequency ratios and absolute frequencies involving seven out of the ten optical clocks currently designated as secondary representations of the second. Several measurements performed in the early stages of the project were submitted to the WGFS in 2020 for use in updating the list of recommended frequency values they maintain. This update, approved by the CCTF in March 2021, was strongly influenced by work carried within the project, in particular our guidelines on the evaluation of correlation coefficients between frequency ratio measurements. As a result of the 2021 update to the list, six secondary representations of the second now have fractional uncertainties below 2×10^{-16}, meaning that they can contribute to TAI with a similar weight to Cs primary frequency standards, if they achieve similar uptimes. Measurements performed later in the project will be submitted to the WGFS ahead of their next update to the list, expected in 2024.

Submission of optical clock data and detailed uncertainty budgets for assessment by the Working Group on Primary and Secondary Frequency Standards (WGPSFS) is expected to lead to approval for inclusion in Circular T, and (at the discretion of the BIPM) subsequent use for TAI steering. The result will be international timescales with improved stability. Two optical clocks from the consortium are now being used for TAI steering, one is pending approval by the WGPSFS as of December 2022, and others have gathered data that will be used for initial submissions.

Reports on the project outputs have also been presented to other working groups of the CCTF. In particular, the results and capabilities demonstrated within the project have influenced the international roadmap towards a redefinition of the SI second, prepared by a new task force set up by the Working Group on Strategic Planning (WGSP).

Longer-term economic, social and environmental impacts

Through its contributions to improving European and global time and frequency infrastructure, this project will bring economic benefits to end users across a wide range of sectors.

Users who are expected to benefit from higher stability reference timescales include the European Space Agency (ESA) and the European VLBI Network (EVN), both of whom operate large-scale facilities that rely on accurate time and frequency signals. Precise time and frequency standards and measurement also lie at the core of many technologies upon which society increasingly relies, the most notable being global navigation satellite systems (GNSS). European companies accounted for 25 % of the global GNSS market in 2015 and timescales with improved stability will further fuel this market by stimulating new applications of GNSS.

Networks of optical atomic clocks will have significant impact in the field of geodesy, as they can be used to measure the Earth's gravity potential with high temporal and spatial resolution via the gravitational redshift of their operating frequencies. In this way it will be possible to bring national height systems into alignment across Europe, as well as to check global and regional geoid models established by other methods. A unified height reference system incorporating measurements made with optical clocks could help prevent costly mistakes in engineering projects. It could also have significant impact on geodynamic and climate research, for example by allowing scientists to track seasonal and long-term trends in ice sheet masses and overall ocean mass changes. Such data provides critical input into models used to study and forecast the effects of climate change.

Accurate time and frequency references underpin numerous technologies that are almost taken for granted in everyday life. Apart from GNSS, systems such as electric power grids, mobile telecommunication networks and the internet all depend on time and frequency standards. The developments realised within this project will enable time and frequency to be disseminated with unprecedented stability and accuracy, not only to end users of the timescales maintained by European laboratories, but also globally through their impact on the international timescales TAI and UTC. As a result, it is expected to have widespread longer-term impact on innovation, science and daily life.

List of publications

1. E. Benkler, B. Lipphardt, T. Puppe, R. Wilk, R. Rohde and U. Sterr. "End-to-end topology for fiber comb based optical frequency transfer at the 10^{-21} level" Optics Express 27, 36886–36902 (2019)

2. M. Pizzocaro, F. Bregolin, P. Barbieri, B. Rauf, F. Levi and D. Calonico. "Absolute frequency measurement of the ${}^1S_0$ – ${}^3P_0$ transition of ^{171}Yb with a link to International Atomic Time" Metrologia 57, 035007 (2020)

3. H. A. Fürst, C.-H. Yeh, D. Kalincev, A. P. Kulosa, L. S. Dreissen, R. Lange, E. Benkler, N. Huntemann, E. Peik and T. E. Mehlstäubler. "Coherent excitation of the highly forbidden electric octupole transition in ^{172}Yb$^+$" Physical Review Letters 125, 163001 (2020)

4. R. Schwarz, S. Dörscher, A. Al-Masoudi, E. Benkler, T. Legero, U. Sterr, S. Weyers, J. Rahm, B. Lipphardt and C. Lisdat. “Long term measurement of the ^{87}Sr clock frequency at the limit of primary Cs clocks” Physical Review Research 2, 033242 (2020)

5. R. Lange, N. Huntemann, C. Sanner, H. Shao, B. Lipphardt, C. Tamm and E. Peik “Coherent suppression of tensor frequency shifts through magnetic field rotation” Physical Review Letters 125, 143201 (2020)

6. J. Lodewyck, R. Le Targat, P.-E. Pottie, E. Benkler, S. Koke and J. Kronjäger. “Universal formalism for data sharing and processing in clock comparison networks”. Physical Review Research 2, 043269 (2020)

7. S. Dörscher, N. Huntemann, R. Schwarz, R. Lange, E. Benkler, B. Lipphardt, U. Sterr, E. Peik and C. Lisdat.“Optical frequency ratio of a ^{171}Yb^{+} single-ion clock and a ^{87}Sr lattice clock” Metrologia 58, 015005 (2021)

8. R. Lange, N. Huntemann, J. M. Rahm, C. Sanner, H. Shao, B. Lipphardt, C. Tamm, S. Weyers and E. Peik. “Improved limits for violations of local position invariance from atomic clock comparisons” Physical Review Letters 126, 011102 (2021)

9. M. Pizzocaro, M. Sekido, K. Takefuji, H. Ujihara, H. Hachisu, N. Nemitz, M. Tsutsumi, T. Kondo, E. Kawai, R. Ichikawa, K. Namba, Y. Okamoto, R. Takahashi, J. Komuro, C. Clivati, F. Bregolin, P. Barbieri, A. Mura, E. Cantoni, G. Cerretto, F. Levi, G. Maccaferri, M. Roma, C. Bortolotti, M. Negusini, R. Ricci, G. Zacchiroli, J. Roda, J. Leute, G. Petit, F. Perini, D. Calonico and T. Ido. “Intercontinental comparison of optical atomic clocks through very long baseline interferometry”. http://hdl.handle.net/11696/64130

10. C. Lisdat, S. Dörscher, I. Nosske and U. Sterr. “Blackbody radiation shift in strontium lattice clocks revisited”. Phys. Rev. Research 3, L042036 (2021)

11. S. Condio. “Optical lattice clock with an amplified laser diode”. Master thesis in physics at University of Torino (2021)

12. L. Seppäläinen. “Reducing the statistical and systematic uncertainty of the VTT MIKES ^{88}Sr^{+} ion clock”. Master thesis in Engineering Physics from Aalto University (2021)

13. M. Schioppo, J. Kronjäger, A. Silva, R. Ilieva, J. W. Paterson, C. F. A. Baynham, W. Bowden, I. R. Hill, R. Hobson, A. Vianello, M. Dovale-Álvarez, R. A. Williams, G. Marra, H. S. Margolis, A. Amy-Klein, O. Lopez, E. Cantin, H. Álvarez-Martínez, R. Le Targat, P. E. Pottie, N. Quintin, T. Legero, S. Häfner, U. Sterr, R. Schwarz, S. Dörscher, C. Lisdat, S. Koke, A. Kuhl, T. Waterholter, E. Benkler and G. Grosche. “Comparing ultrastable lasers at 7´10^{-17} fractional frequency instability through a 2220 km optical fibre network”. Nature Communications 13, 212 (2022)

14. V. Formichella, L. Galleani, G. Signorile and I. Sesia. “Robustness tests for an optical time scale”. Metrologia 59, 015002 (2022)

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

16. C. Clivati, M. Pizzocaro, E. K. Bertacco, S. Condio, G. A. Costanzo, S. Donadello, I. Goti, M. Gozzelino, F. Levi, A. Mura, M. Risaro, D. Calonico, M. Tønnes, B. Pointard, M. Mazouth-Laurol, R. Le Targat, M. Abgrall, M. Lours, H. Le Goff, L. Lorini, P.-E. Pottie, E. Cantin, O. Lopez, C. Chardonnet and A. Amy-Klein. “Coherent optical-fiber link across Italy and France”. Phys. Rev. Applied 18, 054009 (2022)

17. M. B. K. Tønnes, F. Schuller, E. Cantin, O. Lopez, R. Le Targat, A. Amy-Klein and P.-E. Pottie. “Coherent fiber links operated for years: effect of missing data”. Metrologia 59, 065004 (2022)

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1st May 2019 (42 months)</td></tr>
<tr><td colspan="3">Coordinator: Helen Margolis, NPL Tel: 020 8943 6113 E-mail: helen.margolis@npl.co.uk
Project website address: http://empir.npl.co.uk/rocit/</td></tr>
<tr><td>Internal Funded Partners:
1. NPL, United Kingdom
2. CMI, Czechia
3. GUM, Poland
4. INRIM, Italy
5. LNE, France
6. OBSPARIS, France
7. PTB, Germany
8. VTT, Finland</td><td>External Funded Partners:
9. BGU, Israel
10. CNRS, France
11. LUH, Germany
12. POLITO, Italy
13. SRC PAS, Poland
14. UMK, Poland</td><td>Unfunded Partners:</td></tr>
<tr><td colspan="3">Linked Third Parties: 15. CNRS, France (linked to OBSPARIS), 16. UP13, France (linked to CNRS)</td></tr>
<tr><td colspan="3">RMG1: ROA, Spain (Employing organisation); NPL, United Kingdom (Guestworking organisation)
RMG2: ROA, Spain (Employing organisation); OBSPARIS, France (Guestworking organisation)</td></tr>
</table>