Final Publishable JRP Summary for SIB55 ITOC
International timescales with optical clocks

Overview

This project has made significant advances in addressing the key steps that must be taken prior to an optical redefinition of the SI second. An extensive programme of comparisons between high accuracy European optical atomic clocks has been performed, leading the way in verifying the estimated uncertainty budgets of optical clocks. Relativistic effects influencing clock comparisons have been evaluated at an improved level of accuracy and the potential benefits that optical clocks could bring to the field of geodesy have been demonstrated.

Need for the project

Time and frequency play a central role within SI because they can be measured more accurately than any other physical quantity. The SI second is currently defined in terms of the frequency of the microwave transition between the two ground state hyperfine levels of the caesium-133 atom. However the most advanced optical atomic clocks have now reached levels of stability and uncertainty that significantly surpass the performance of caesium primary standards, for which the best reported results are an instability of $1.4\times10^{-14}\ \tau^{-1/2}\ s^{1/2}$ (where τ is the averaging time) and an uncertainty of 1.1×10^{-16}. As a result, the possibility of a redefinition of the second in terms of an optical transition frequency is being considered by the international metrology community.

At the start of this project, nearly all information about the reproducibility of optical clocks came from independent absolute frequency measurements made in different laboratories, and was therefore limited by the uncertainty of the local caesium primary standards. A number of challenges therefore remained to be addressed to prepare for an optical redefinition of the second. In particular, improved methods were required for comparing the frequencies of clocks constructed in different laboratories, so that a coordinated programme of clock comparisons could be carried out. Such comparison programmes are essential to build confidence in the new generation of optical clocks by validating their performance levels, to anchor their frequencies to the present definition of the second with the lowest possible uncertainty, and to establish the leading contenders for a new definition of the second. Optical clocks have reported instabilities below $2\times10^{-16}\ \tau^{-1/2}\ s^{1/2}$ and estimated systematic uncertainties as low as 2.0×10^{-18}. These levels of instability and uncertainty mean that, to derive the maximum benefits from incorporating them into international timescales, increased accuracy was required in the application of Einstein's theory of general relativity. To compare the optical clocks at the level of their estimated systematic uncertainties required improved evaluations of relativistic effects influencing the comparison, including shifts due to the local gravitational potential experienced by each clock. Finally, a framework and procedures whereby optical clocks could be integrated into international timescales were required.

Scientific and technical objectives

To address these requirements, this project set out to:

- Compare the frequencies of optical atomic clocks developed within individual NMIs, by direct comparison between clocks based on the same atomic species, or by using femtosecond combs to measure optical frequency ratios between different types of optical clock.
- Compare the frequencies of optical atomic clocks developed by different NMIs at the 10^{-16} - 10^{-17} level of accuracy.
- Make absolute frequency measurements of the optical atomic clocks using femtosecond combs, with uncertainty limited by caesium fountain primary frequency standards.

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- Make a complete evaluation of all relativistic effects influencing time and frequency comparisons between optical atomic clocks at the 10^{-18} level of accuracy.
- Establish a connection to geodetic models in order to describe the variation of the clock frequencies due to changes in the gravity potential.
- Investigate the possibility of using continuously operating transportable optical clocks for the comparison of remote clocks, including a consideration of the effects on the trajectory of the clock during travel.
- Carry out a proof-of-principle experiment using optical clocks to measure gravity potential differences.
- Perform an analysis of the complete frequency ratio measurement matrix derived from the optical clock comparison programme in order to check the consistency of the measurements.
- Based on the frequency ratio measurement matrix, to derive optimised values for the frequency of each optical clock transition relative to the current definition of the SI second.
- Consider other important factors influencing the use of optical clocks as secondary representations of the second for steering of International Atomic Time (TAI) and Coordinated Universal Time (UTC).

Results

Comparison of optical atomic clocks developed within individual NMIs

Several optical frequency ratio measurements have been made locally at NPL, OBSPARIS and PTB, all of whom operate more than one type of optical clock. A particular highlight is the direct ^{199}Hg/^{87}Sr optical frequency ratio measurement performed at OBSPARIS, which has a fractional uncertainty of 1.8×10^{-16}. This result is in good agreement with an independent measurement performed at RIKEN in Japan, and is the first inter-continental agreement between optical frequency ratio measurements with an accuracy beyond that of the realization of the SI second.

Comparison of optical atomic clocks developed by different NMIs

Two techniques for comparing optical atomic clocks developed by different NMIs have been explored, both of which could potentially be applied on an intercontinental scale.

A transportable ^{87}Sr optical lattice clock has been developed at PTB. This has been moved to the collaborator Laboratoire Souterrain de Modane (LSM) and INRIM for two separate measurement campaigns and has successfully been brought to operation, even in the very challenging environmental conditions at LSM. This is the first functional transportable optical clock worldwide and has achieved a better performance than any other mobile frequency standard, both in terms of instability and uncertainty. At VTT, transportable subsystems have been developed for a ^{88}Sr+ trapped ion optical clock.

The second technique investigated was a broadband version of two-way satellite time and frequency transfer (TWSTFT). This was used in June 2015 to carry out by far the most extensive remote optical clock comparison that has ever been performed, in which link uncertainties in the low parts in 10^{16} range were achieved. An unexpected, but significant, result is that the recently introduced GPS integer precise point positioning (IPPP) technique has a similar performance to broadband TWSTFT, but at considerably reduced operational cost. GPS-IPPP has a clear advantage compared to broadband TWSTFT in that it is a robust technique that can readily be put into regular operation.

Absolute frequency measurements of optical atomic clocks

Five independent absolute frequency measurements of ^{87}Sr optical lattice clocks have been completed at PTB, OBSPARIS and NPL, and agreement has been observed between the different clock designs to the level at which the SI second can be realized i.e. a few parts in 10^{16}. An absolute frequency measurement of the newly developed ^{171}Yb optical lattice clock at INRIM has also been performed. Several other results have been obtained from the EMRP project SIB04 - Ion clock: an absolute frequency measurement of the $^{88}Sr^{+}$ trapped ion optical clock and absolute frequency measurements of the E2 and E3 optical clock transitions in the $^{171}Yb^{+}$ ion. These results have fed into the overall consistency analysis of the clock comparison results.

Evaluation of relativistic effects influencing time and frequency comparisons

Evaluation of the relativistic effects relevant for TWSTFT has provided critical input to the clock comparison campaign using a broadband version of this technique. A physical model has also been formulated to describe the relativistic effects relevant to time and frequency transfer over optical fibre links, and has been used to evaluate the relativistic corrections for the fibre links now in place between NPL, OBSPARIS and PTB, as well as to provide guidelines on the importance of exact fibre routing for time and frequency transfer via optical fibre links.

Connection to geodetic models

The gravity potential has been determined with significantly improved accuracy at the sites participating in optical clock comparisons within the project. A technical report written by LUH sets out the theoretical background for deriving the gravity potential and makes recommendations for the levelling and GNSS observations that must be made at the clock sites. Based on these recommendations, levelling measurements have been performed at INRIM, LSM, OBSPARIS, NPL and PTB. Gravity surveys have also been carried out by LUH at all these locations, including at least one absolute gravity observation on each site and between 35 and 122 relative gravity measurements around each site. These measurements have been integrated into the existing European gravity database and used to compute a new version of the European Gravimetric (Quasi) Geoid, EGG2015. Time-variable gravity potential signals induced by tides and non-tidal mass redistributions have also been calculated for the optical clock comparison sites.

The potential contributions of optical clock measurements for determining the gravity potential at high spatial resolution (length scales ≈10 km) have also been studied theoretically. Simulations show that adding even a few data points from optical clocks in areas where gravity information is poor can reduce the bias and improve by a factor of about 2 the standard deviation of the geoid determination.

Possibility of using continuously operating transportable optical clocks for the comparison of remote clocks

The relativistic effects relevant to transportation of a continuously operating optical clock by land, air or sea have been evaluated. Realistic paths along which continuously operating optical clocks might be transported were considered, between PTB and NPL, between PTB and OBSPARIS and between LSM and INRIM. Depending on the quality of the navigation system used, we conclude that the uncertainty of the relativistic corrections would be at the level of 0.01 – 1 ps.

Proof-of-principle experiment using optical clocks to measure gravity potential differences

A proof-of-principle experiment has been realized to show that the gravitational redshift of optical clocks can be exploited to measure gravity potential differences over medium–long baselines. The transportable strontium optical lattice clock developed at PTB was transported to LSM in the Fréjus road tunnel through the Alps between France and Italy. There it was compared using a transportable frequency comb from NPL to the caesium fountain primary frequency standard at INRIM, via a coherent fibre link and a second optical frequency comb operated by INRIM. The gravity potential difference determined from the clock comparison is consistent with the potential difference determined by LUH using conventional geodetic methods.

Analysis of the frequency ratio measurement matrix derived from the optical clock comparison programme

New methods have been developed for analysing over-determined sets of clock frequency comparison data involving standards based on a number of different reference transitions. A least-squares adjustment procedure was used, based on the methods used by CODATA to provide a self-consistent set of internationally recommended values of the fundamental physical constants. Analysis software has been developed that can be used to derive optimised values for the frequency ratios of all possible pairs of reference transitions, including absolute frequency values as the special case of frequency ratios involving the caesium ground-state hyperfine transition. The software also performs self-consistency checks on the input data set.

Optimised values for the frequency of each optical clock transition

The software developed was used to analyse the complete body of clock frequency comparison data submitted to the CCL-CCTF Frequency Standards Working Group (WGFS) in September 2015, which included both data generated by this project consortium and results from other groups around the world. The results were used by the CCL-CCTF WGFS to derive updated recommended frequency values and uncertainties for secondary representations of the second. These values were approved by the CIPM in October 2015 and have subsequently been published on the BIPM website.

Other important factors influencing the use of optical clocks for steering of TAI and UTC

If optical clocks are to make regular contributions to international timescales, it is vital that methods are available for bridging outages in optical clock operation and link operation with negligible influence on the stability of the time scale. Within this project it has been shown that sufficiently stable hydrogen masers or optical cavities can be used as flywheel oscillators to bridge surprisingly long gaps in optical clock data without degrading clock comparison uncertainties. Simulations have shown that a local timescale based on an optical clock with limited availability (< 50%) can have long-term performance better than one using the best present-day caesium fountain standards, even if those standards are operated without any interruptions.

Actual and potential impact

Dissemination

The potential uptake of the project results by end users has primarily been promoted by a range of dissemination activities such as more than 85 presentations at conferences and workshops, the project website, and input to metrology committees. A one-week summer school was held in June/July 2015 and a final international workshop was held in association with the 2016 European Frequency and Time Forum (EFTF 2016). This workshop was attended by more than 70 people, including a number from NMIs outside Europe (NIST, NRC, NMIJ and KRISS) as well as representatives from BIPM, European SMEs and the geodesy community.

Thus far 17 papers have been published in the public domain and several more are in preparation. Most are papers in specialist journals, but a commentary article “Timekeepers of the future” was also written for Nature Physics. In addition to papers written by members of our consortium, a news article “Hyper-precise atomic clocks face off to redefine time” appeared in Nature, whose news editor’s attention was attracted by our campaign to compare optical clocks at INRIM, NPL, OBSPARIS and PTB via satellites. The ITOC project coordinator and one of the partners were both interviewed and quoted in the article.

Impact on the metrological and scientific communities

The most direct impact of this project is on the top-level realisation and dissemination of the SI unit of time, in providing results and procedures to prepare for a future redefinition of the second. This impact has been achieved by input to the Consultative Committee for Time and Frequency (CCTF) and its associated working groups, in particular the Frequency Standards Working Group (WGFS). The least-squares analysis methods and absolute frequency and optical frequency ratio measurements performed in this project had a significant impact on the latest updates to the International Committee for Weights and Measures (CIPM) list of recommended frequency values, prepared by the WGFS in September 2015. The results and capabilities demonstrated within the project have also influenced the international roadmap towards a redefinition of the SI second, recently prepared by the CCTF Working Group on Strategic Planning.

Key results 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 in the new generation of optical clocks both in the metrology community and beyond. The verification of optical clock performance levels will allow the international community to make better informed decisions regarding a future redefinition of the second, and will potentially allow the community to identify the most promising candidates for such a redefinition, focussing future primary standard development on a smaller number of systems. Important results have also been obtained that pave the way for future intercontinental clock comparison experiments.

The international scientific community will benefit from validated clock comparisons as a basis for tests of fundamental physical theories. One example is the search for temporal variation of the fine structure constant by comparing transition frequencies in different optical clocks. The demonstrated performance of the ground-based optical clocks and the lessons learned from the satellite-based clock comparison techniques explored within this project will also benefit fundamental science space missions such as ACES (Atomic Clock Ensemble in Space), which is due to be launched in 2018.

The proof-of-principle experiment carried out within this project has demonstrated that optical clocks can be used to make direct measurements of the Earth's gravity potential. High-resolution measurements made at well-defined locations using transportable optical clocks could bring significant benefits to the geodesy community in terms of achieving a consistent alignment of national height systems within Europe, as well as checks of global and regional geoid models established by alternative means. Such measurements would also complement the data obtained from satellite missions such as Gravity field and steady-state Ocean Circulation Explorer (GOCE) or Gravity Recovery and Climate Experiment (GRACE), which provide global coverage but give values that are spatially averaged over length scales of about 100 km. The gravity measurement campaigns undertaken within the project have already benefitted other metrology experiments such as the cold atom gravimeter and watt balance experiments at OBSPARIS.

Impact on industrial and other user communities

The information and experience gained during the broadband TWSTFT optical clock comparison campaign has been shared with a European manufacturer of time and frequency equipment who collaborated on this part of the work, and is expected to feed into their future product improvements.

Time and frequency references underpin numerous technologies that we have come to take for granted in everyday life, particularly in the areas of communication and navigation. The developments realised within this project will in the longer term enable time and frequency to be disseminated with unprecedented stability to end users of international timescales. In this way, the high stability and low uncertainties of optical clocks, confined today to national measurement institutes, will be made available to industry, leading to widespread impact on innovation, science and daily life.

List of publications

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