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1 Executive Summary

Introduction

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 the optical clocks. Relativistic effects influencing clock comparisons have been evaluated at an improved level of accuracy and the benefits that optical clocks could bring to geodesy have been demonstrated.

The Problem

The most advanced optical atomic clocks have now reached levels of stability and uncertainty that significantly surpass the performance of the best caesium primary frequency standards. 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.

Before an optical definition of the second can be implemented, it is necessary to address the problem of comparing the frequencies of optical clocks constructed in different laboratories at a level commensurate with the clock performance. Such comparisons are essential to build confidence in the new generation of clocks by validating their performance levels and to establish the leading contenders for a new definition.

The Solution

This project set out to tackle these challenges by developing new methods for comparing optical clocks developed in different laboratories, focussing on techniques which have the potential to be applied on an intercontinental scale. These methods were applied in a coordinated programme of clock comparisons, which was performed to validate the uncertainty budgets of the optical clocks and to anchor their frequencies to the present definition of the second. To support this comparison programme we evaluated relativistic effects influencing time and frequency comparisons between clocks at an improved level of accuracy, including shifts due to the local gravity potential experienced by each clock. We also considered a framework and procedures whereby the optical clocks could in future be integrated into international timescales.

Impact

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 associated working groups, in particular the Frequency Standards Working Group (WGFS). 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.

Results from our frequency comparison experiments were submitted to the WGFS in September 2015 to be considered in their task of updating the CIPM list of recommended frequency values. Analysis methods and software developed within this project enabled the WGFS to make full use of the available over-determined set of clock frequency comparison data to derive optimized frequency values for each standard.

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 project has helped to build confidence in the new generation of optical clocks both in the metrology community and beyond. This will allow the international metrology community to make better informed decisions regarding a future redefinition of the second, and will potentially enable the most promising candidates for such a redefinition to be identified, so that future development can focus on a smaller number of systems. Important results have also been obtained that pave the way for future intercontinental optical clock comparisons.

The international scientific community will benefit from validated clock comparisons as a basis for tests of fundamental physical theories. This project has also demonstrated the benefits that optical clocks could bring to the geodesy community, where they could be used to achieve a consistent alignment of national height systems as well as improvements to regional geoid models. In the longer term, the developments realised within this project will enable time and frequency to be disseminated with unprecedented stability to end users of international timescales, which can be expected to lead to widespread impact on innovation, science and daily life.

2 Project context, rationale and objectives

Time and frequency play a central role within the International System of measurement (SI) because they can be measured more accurately than any other physical quantity. The realisation of the SI unit of time is already used in the realisations of the metre, the volt and the ampere, and will play an even more prominent role in the revised SI, which will be based on constants of nature. In this revised system, the definitions of all SI base units (except for the mole) will make explicit reference to the definition of the second¹.

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. The international timescales TAI (International Atomic Time) and UTC (Coordinated Universal Time) are constructed using data from microwave atomic clocks in approximately 70 institutions worldwide, which are compared by satellite-based time and frequency transfer techniques. Data from caesium primary frequency standards are used whenever available to apply steering corrections, ensuring that the scale interval of TAI and UTC remains as close as possible to the SI second. The best performance levels so far reported for caesium fountain primary standards are a fractional frequency instability of $1.4 \times 10^{-14} (\tau/s)^{-1/2}$ (where τ is the averaging time in seconds) and an estimated fractional uncertainty of 1.1×10^{-16} .

However, the most advanced optical atomic clocks have now reached a level of performance that clearly exceeds that of the best primary caesium atomic clocks, both in terms of instability and estimated systematic uncertainty. Instabilities below $2 \times 10^{-16} (\tau/s)^{-1/2}$ have been reported, as well as estimated systematic uncertainties as low as 2×10^{-18} . These developments raise the question of whether or not the caesium-133 atom provides the best possible basis for the definition of the unit of time, and the possibility of a future redefinition of the SI second in terms of an optical transition frequency is being actively considered by the international metrology community. However, many different optical clock transitions are currently being investigated and at present none of these clearly stands out from the rest as a natural candidate for such a redefinition. Before a decision can be made, significant work is required to assess the fundamental limits to the stability and accuracy that can be achieved for each system. In European National Metrology Institutes (NMIs), the optical clocks being studied include those based on ⁸⁷Sr, ⁸⁸Sr⁺, ¹⁷¹Yb⁺, ¹⁷¹Yb and ¹⁹⁹Hg.

In the meantime, to prepare for a future redefinition, the International Committee for Weights and Measures (CIPM) has introduced the concept of secondary representations of the second. At the present time, seven different optical transitions can be used in this way². These alternative realisations of the SI second cannot be any more accurate than the best caesium standards of today, but allowing them to contribute at some level to international timescales was seen by the CIPM as a way to encourage NMIs to invest in the development of optical standards. However, although the concept of secondary representations has been established, none of the optical clocks included in the list is yet contributing to international timescales in practice. For this to happen, it is necessary to build confidence in the new generation of optical clocks and to establish a framework and robust procedures whereby they can be integrated into international timescales. Since unprecedented levels of stability and accuracy are being investigated with the new generation of optical atomic clocks, reliable evaluations of their uncertainty budgets and further improvements to the clocks can only be made by comparing their frequencies directly, free of the limitations imposed by caesium primary standards.

At the start of this project, very few direct frequency comparisons between optical clocks had been carried out, and those that had been almost all involved comparing two similar clocks developed within a single laboratory. Although such tests have an important role to play, a much more stringent test of clock performance is to compare optical clocks developed independently by different laboratories. This type of comparison almost exclusively involved comparing absolute frequency measurements made in different laboratories, and the information that could be extracted about reproducibility was therefore limited by the uncertainties associated with the caesium fountain primary standards used as local realisations of the SI second.

A coordinated programme of direct frequency comparisons between the highest accuracy optical clocks was therefore required, both locally (between optical clocks developed by individual NMIs) and remotely (between clocks developed by different NMIs). Furthermore, there needed to be sufficient redundancy in this

¹ I. M. Mills, P. J. Mohr, T. J. Quinn, B. N. Taylor and E. R. Williams, "Adapting the International System of Units to the twenty-first century", *Phil. Trans. R. Soc. A* 369, 3907–3924 (2011).

² "Recommended values of standard frequencies", <http://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html>

comparison programme to allow internal consistency checks to be performed. These requirements were recognised by the 23rd General Conference on Weights and Measures (CGPM) in 2007, which recommended (resolution 9) that NMIs should commit resources to the development of optical frequency standards and their comparison³, and were further strengthened by the 24th CGPM (2011) with their recommendation (resolution 8) that the International Bureau of Weights and Measures (BIPM) should support the coordination of an international project with the participation of NMIs, oriented to the study of techniques that could serve to compare optical frequency standards⁴. A comprehensive set of absolute frequency measurements with uncertainties at the limit set by caesium primary standards was also required to anchor the frequencies of the optical clocks to the present definition of the second. This will maximise the potential contribution to TAI prior to a redefinition, and will also ensure that no discontinuity is introduced at the point of redefinition.

The levels of stability and uncertainty reached by the optical clocks had reached the point 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 necessary level of accuracy required improved evaluations of relativistic effects influencing the comparison, such as the Sagnac effect, the velocity of the clocks with respect to an inertial reference frame and the gravitational redshift of the clock transition frequency. The last point required contributions from the international geodesy community so that the necessary connection to geodetic models can be established.

Beyond the metrology community, optical clocks offer opportunities to push tests of fundamental physical theories to new levels, as clearly identified in the scientific and technological roadmap drawn up by the Fundamental Physics Roadmap Advisory Team for the European Space Agency (ESA)⁵. For example, progress in experiments designed to search for violation of the Einstein Equivalence Principle by looking for temporal changes in fundamental physical constants is directly dependent on atomic clocks with improved stability and accuracy. High accuracy ground clocks and methods for their comparison are similarly required to support proposed fundamental space missions such as ACES (Atomic Clock Ensemble in Space).

In the field of geodesy, it is well known that the national height systems across Europe differ by more than 0.5 m. Furthermore, traditional levelling methods are not capable of bridging the oceans and new methods are needed to bring the systems into alignment. The use of high accuracy optical clocks to make direct measurements of the gravitational potential with high spatial and temporal resolution, termed clock-based geodesy, offers one possible approach to meeting this need. Such measurements would complement the data available from satellite missions such as GRACE (Gravity Recovery and Climate Experiment) or GOCE (Gravity field and steady-state Ocean Circulation Explorer), which provide data with nearly global coverage and with an accuracy equivalent to centimetre height accuracy, but averaged over length scales of order 100 km.

Bearing in mind these requirements, this project set out to develop new methods for comparing optical clocks developed in different laboratories, focussing on techniques which have the potential to be applied on an intercontinental scale. The specific scientific and technical objectives of this project were:

1. 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.
2. To compare the frequencies of optical atomic clocks developed by different NMIs at the 10^{-16} - 10^{-17} level of accuracy using transportable optical clocks, fibre links and broad bandwidth satellite links.
3. To make absolute frequency measurements of the optical atomic clocks using femtosecond combs, with uncertainty limited by caesium fountain primary frequency standards, in order to link their frequencies as accurately as possible to the current definition of the SI second.
4. To make a complete evaluation of all relativistic effects influencing time and frequency comparisons between optical atomic clocks at the 10^{-18} level of accuracy.

³ Text of the resolutions adopted by the 23rd General Conference on Weights and Measures (2007), <http://www.bipm.org/utis/en/pdf/Resol23CGPM-EN.pdf>

⁴ Resolutions adopted by the General Conference on Weights and Measures (24th meeting), Paris, 17–21 October 2011, http://www.bipm.org/utis/common/pdf/24_CGPM_Resolutions.pdf

⁵ ESA-appointed Fundamental Physics Roadmap Advisory Team, "A Roadmap for Fundamental Physics in Space" (2010), <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47598>

5. To establish a connection to geodetic models in order to describe the variation of the clock frequencies due to changes in the gravity potential.
6. To 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.
7. To carry out a proof-of-principle experiment using optical clocks to measure gravity potential differences.
8. To 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.
9. 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.
10. To consider other important factors influencing the use of optical clocks as secondary representations of the second for steering of TAI and UTC, including uncertainties arising from the dead time of the standards and the techniques used to compare the clocks.

3 Research results

A major part of the work performed within this project involved a tightly integrated programme of frequency comparisons between European optical clocks (Figure 1), with the aim of progressing beyond the state of the art by achieving comparison uncertainties better than the level at which the present definition of the SI second can be realised. This programme involved three fundamentally different types of comparisons: comparisons between optical clocks developed within individual NMIs (section 3.1), comparisons between optical clocks developed by different NMIs (section 3.2) and absolute frequency measurements of the optical clocks relative to caesium primary standards (section 3.3). The comparison programme included sufficient redundancy to allow internal self-consistency checks to be performed. For this purpose, and to derive optimised frequency ratio values between all pairs of standards involved in the clock comparison programme, new methods were developed for analysing over-determined sets of clock frequency comparison data (sections 3.8 and 3.9).

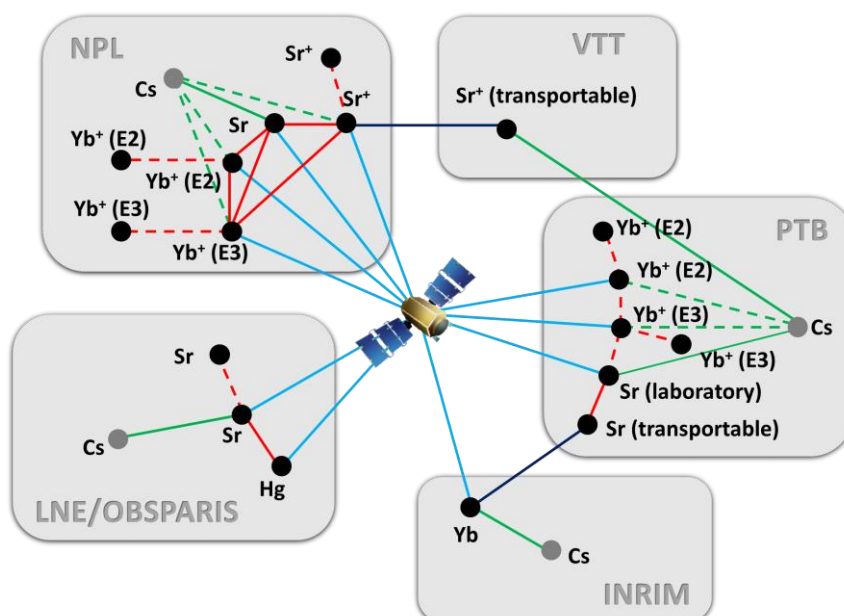


Figure 1. ITOC clock comparison programme, involving local optical frequency ratio measurements (red) and absolute frequency measurements (green) within individual NMIs, as well as remote frequency comparisons via broad bandwidth two-way satellite time and frequency transfer (light blue) and using transportable clocks (dark blue). Dotted lines indicate measurements carried out within other projects but that were included in the self-consistency analysis performed within the ITOC project.

Other parts of the work undertaken addressed the need for increased accuracy in the application of Einstein's theory of relativity and have led to a complete theoretical evaluation of all relativistic effects influencing time and frequency comparisons at the 10^{-18} level of accuracy, including the gravitational redshift of the optical clock frequencies (sections 3.4 – 3.6). Important factors influencing the use of optical clocks for steering timescales have also been studied (section 3.10).

The bulk of the research performed is thus of most direct relevance to the international metrology community, in preparing for a future redefinition of the SI second. However, we have also demonstrated the impact that high accuracy optical atomic clocks with clearly verified levels of performance could have on the field of geodesy, by carrying out a proof-of-principle experiment in which a transportable optical clock was used to measure the gravity potential difference between two sites (section 3.7).

3.1 Comparison of optical atomic clocks developed within individual NMIs

Local frequency comparisons between optical clocks, with fractional uncertainties reaching down to the parts in 10^{17} level, have been carried out at NPL, OBSPARIS and PTB, all of whom operate more than one type of optical clock.

The technique used for these local frequency comparisons between optical clocks operating at different frequencies involves using a femtosecond optical frequency comb to measure the frequency ratio between the two clock frequencies. Comparing optical clocks directly under local laboratory conditions leads to the highest possible levels of both stability and accuracy for the measurements. Femtosecond combs have previously been shown to support optical frequency comparisons at the 10^{-18} level or even lower, avoiding the limitations associated with the uncertainty of primary frequency standards. The actual uncertainty achieved for each comparison was thus limited in practice by the uncertainty associated with each optical standard at the time of the comparison. The key challenge was therefore to characterise and reduce the uncertainties associated with each optical frequency standard, and this was carried out with a series of auxiliary measurements and associated improvements in the setups for each optical clock.

The local optical frequency ratios that were measured during the project involved all the operational optical clocks at NPL, OBSPARIS and PTB, i.e. the ^{199}Hg , ^{87}Sr , $^{88}\text{Sr}^+$ and $^{171}\text{Yb}^+$ (E2 & E3) standards. All except the ^{199}Hg standard have already been accepted as secondary representations of the second and the measurements performed in this project will make a significant contribution to assessing their performance as candidates for a future redefinition of the second. One of the optical frequency ratio measurements (between the E2 and E3 clock transitions in $^{171}\text{Yb}^+$) carried out in this project was included in the frequency ratio matrix analysis performed for the CCL-CCTF Frequency Standards Working Group in September 2015 (section 3.9), and thus contributed to the updates to the list of recommended frequency values adopted by the CIPM following that meeting. The results of the other optical frequency ratio measurements were not available at that time, but can be expected to be included in the next analysis, which is due to be carried out in the run-up to the next CCTF meeting in June 2017.

A particular highlight amongst the local optical frequency ratio measurements performed within this project is the measurement of the $^{199}\text{Hg}/^{87}\text{Sr}$ optical frequency ratio at OBSPARIS⁶, for which the experimental setup is shown in Figure 2. In this measurement the overlap in the up-times for the two optical clocks was 36.6 hours. The frequency instability of the optical-optical comparison is consistent with white frequency noise at the level of $4 \times 10^{-15} \tau^{-1/2}$ for timescales up to about 2 hours. For longer timescales frequency flicker noise of around 5×10^{-17} is observed, below the present accuracy of the ^{199}Hg clock. The final value for the optical frequency ratio between the two clocks has a fractional uncertainty of 1.8×10^{-16} , and is dominated by the systematic uncertainty of the ^{199}Hg lattice clock, with the ^{87}Sr lattice clock contributing only 4.1×10^{-17} . The 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.

⁶ R. Tyumenev, M. Favier, S. Bilicki, E. Bookjans, R. Le Targat, J. Lodewyck, D. Nicolodi, Y. Le Coq, M. Abgrall, J. Guéna, L. De Sarlo and S. Bize, "Comparing a mercury optical lattice clock with microwave and optical frequency standards", arXiv:1603.02026 (2016)

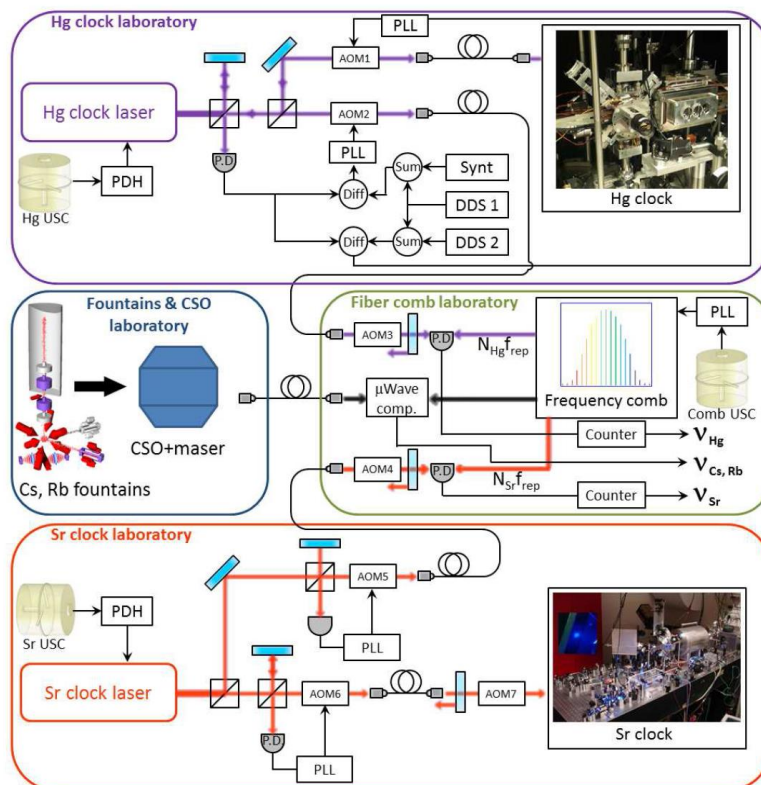


Figure 2. Scheme used to compare the frequencies of the ^{199}Hg and ^{87}Sr optical lattice clocks at OBSPARIS, and also to compare their frequencies to those of the microwave Cs and Rb fountains. Both the optical-optical and the optical-microwave frequency comparisons are performed using a femtosecond comb, with a fraction of the probe laser light for each clock being sent to the comb via frequency stabilised optical fibre links.

3.2 Comparison of optical atomic clocks developed by different NMIs

Although it has already been shown that optical fibre links provide a means for comparing the frequencies of optical clocks on the same continent at a level compatible with their estimated systematic uncertainties, there is presently no clear route towards extending this capability to intercontinental clock comparisons. Within this project we therefore focussed our attention on two alternative approaches, which could potentially be applied on an intercontinental scale. These are the use of transportable optical clocks and improved versions of the satellite-based time and frequency transfer techniques routinely used to compare microwave atomic clocks. Both approaches have proved capable of achieving uncertainties in the low parts in 10^{16} range, which represents a significant improvement on the previous state of the art.

Transportable optical clocks

At PTB, a transportable ^{87}Sr optical lattice clock has been developed. In contrast to transportable optical clocks being developed in other projects such as the FP7 “Space Optical Clocks” project, where the background of space applications means that the mass, size and power consumption of the clocks is of prime importance, the goal of the PTB work was to develop a clock with stability and uncertainty as close as possible to state-of-the-art laboratory optical clocks.

An initial evaluation of the transportable lattice clock was performed at PTB by comparison against their laboratory lattice clock. The ^{87}Sr clock transition can be resolved in the transportable apparatus with a linewidth of 6 Hz (full width at half maximum) and high contrast (Figure 3a). These scans and the observed instability in the comparison against the laboratory lattice clock (Figure 3b) are well within the design expectations. In particular, the transportable clock laser comes close to reaching the performance of the most recent laboratory ones, with only a small trade-off in performance having to be accepted in order to meet the requirements of compactness and shock resistance. A fractional uncertainty below 10^{-16} was achieved for the transportable clock and confirmed by comparison with the laboratory clock.

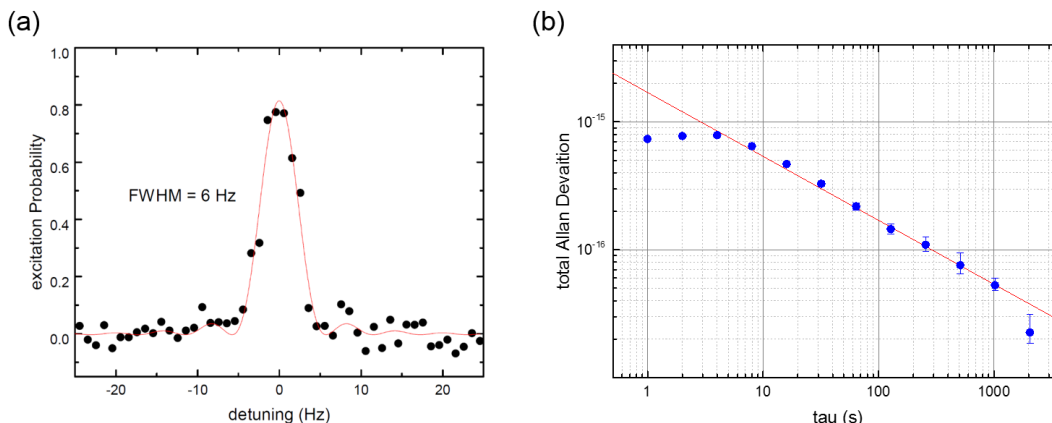


Figure 3. (a) The ⁸⁷Sr clock transition at 429 THz, as observed in the transportable lattice clock. (b) Fractional frequency instability of the transportable ⁸⁷Sr lattice clock, as determined by comparison against a more stable laboratory lattice clock.

Following its initial evaluation, the transportable ⁸⁷Sr optical lattice clock was installed in a temperature-controlled trailer (Figure 4) and moved to the collaborator Laboratoire Souterrain de Modane (LSM) and INRIM for two separate measurement campaigns. In both locations transportable lattice clock was successfully brought to operation, even in the very challenging environmental conditions at LSM where temperature fluctuations were much larger and background noise levels were much higher than in a metrology laboratory setting. At LSM, the clock was used for a proof-of-principle experiment to show that optical clocks could be used to measure the gravity potential difference between two remote locations (section 3.7). At INRIM, a comparison with the local ¹⁷¹Yb optical lattice clock was performed, leading to a direct evaluation of the frequency ratio between the ¹⁷¹Yb and ⁸⁷Sr optical clock transitions. This measurement can be compared with the same optical frequency ratio measured by comparing optical clocks in Japan, providing a test of the consistency between optical clocks developed in different continents.

The PTB clock is the first functional transportable optical lattice clock worldwide and has achieved a performance better than that of any other mobile frequency standard, both in terms of instability and uncertainty.

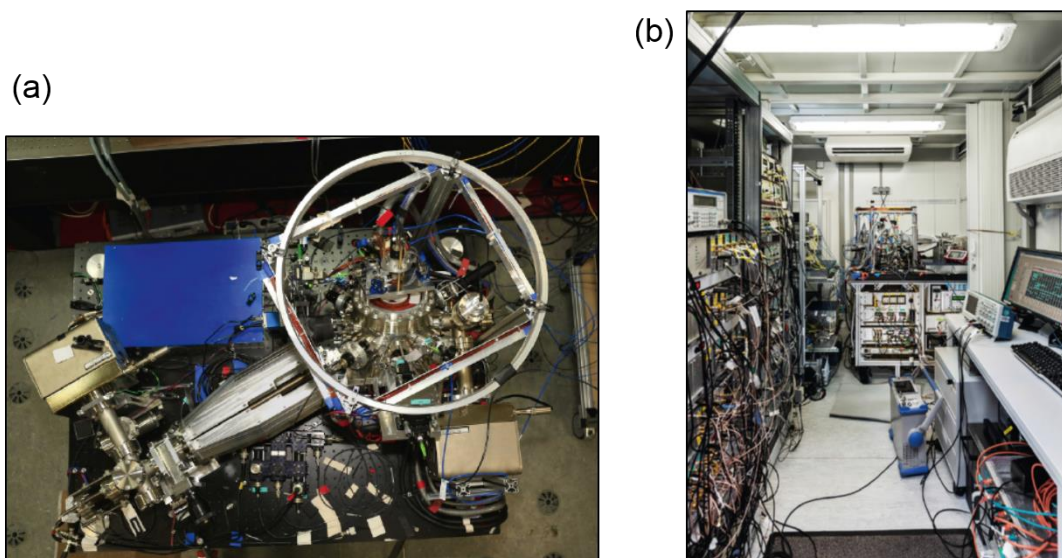


Figure 4. (a) Physics package of the transportable strontium optical lattice clock. (b) Interior of the trailer housing the experiment.

At VTT, work has focussed on an alternative type of optical clock technology, with a transportable physics package being developed for a $^{88}\text{Sr}^+$ trapped ion optical clock (Figure 5). In future this could be taken to NPL for a direct comparison with independently developed $^{88}\text{Sr}^+$ optical clocks.

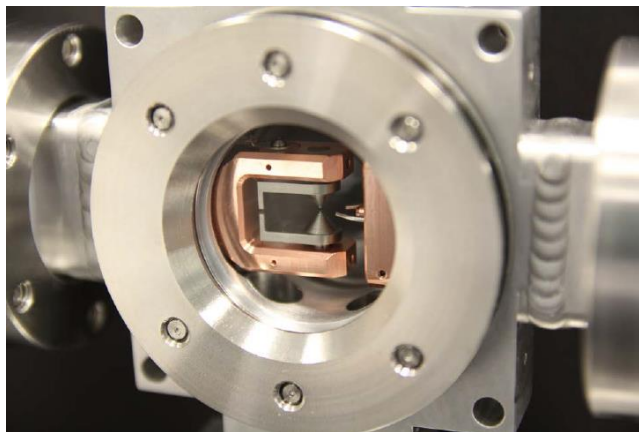


Figure 5. Transportable physics package for a $^{88}\text{Sr}^+$ optical clock, developed at VTT.

Broadband TWSTFT

The second technique investigated during the project was a broadband version of two-way satellite time and frequency transfer (TWSTFT). The TWSTFT links currently used in the computation of TAI are based on a bit rate of 1 MChip/s. In this new work, experiments were performed with a chip rate of 20 MChip/s, with the goal being a reduction of instability of one order of magnitude compared to the routinely employed methods, from around 10^{-15} to 10^{-16} after one day of averaging.

The setup used for these experiments is shown in Figure 6. The broadband TWSTFT measurements were used to compare the frequencies of reference active hydrogen masers in the laboratories at each end of a link. In addition, and as an independent method, GPS (global positioning system) frequency comparisons were also performed using the precise point positioning (PPP) concept. Optical clock comparisons were performed by measuring simultaneously the frequencies of the optical clocks at each of the participating laboratories (INRIM, NPL, LNE/OBSPARIS and PTB) directly against the local reference maser, using femtosecond optical frequency combs.

Running TWSTFT links with a chip rate of 20 MChip/s required the consortium to lease a dedicated Ku-band transponder on a geostationary satellite (the SES ASTRA 3B satellite). Due to the high cost of the transponder lease, only one month could be afforded within the project budget, and this was split into two parts: a one-week link test campaign performed in October 2014, and a three-week optical clock comparison campaign performed in June 2015.

The experiment carried out within this project is by far the most extensive remote optical clock comparison that has ever been performed, involving seven different optical clocks in four different laboratories. ^{87}Sr optical lattice clocks were operated at NPL, OBSPARIS and PTB, $^{171}\text{Yb}^+$ trapped ion optical clocks were operated on the E3 transition at NPL and PTB, the ^{199}Hg optical lattice clock was operated at OBSPARIS and INRIM contributed their newly operational ^{171}Yb optical lattice clock. The measurement campaign was also supported by caesium fountain primary frequency standards operating in three out of the four laboratories (INRIM, OBSPARIS and PTB). The desire to gather as much clock comparison data as possible in a limited period of time proved a powerful stimulus to improve the robustness of the optical clocks. During the campaign, several of the optical clocks were operational for up to almost 90% of the time (Figure 7), not all that far behind the regularly operated caesium primary standards. These high operational duty cycles are an important technical prerequisite for optical clocks to make useful contributions to international timescales.

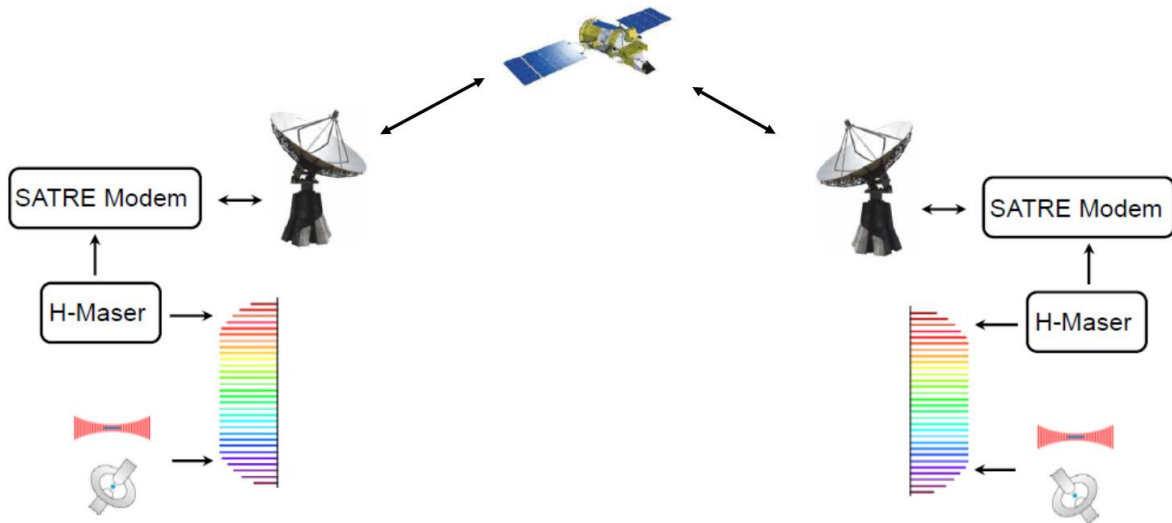


Figure 6. Experimental setup for optical clock comparisons via the broadband TWSTFT link.

Problems were experienced at the start of the June 2015 measurement campaign due to unexpected interference from a ground-based signal in Paris at a frequency close to that being used for the downlink. This necessitated a change to a different satellite transponder, which could not be implemented immediately by the satellite provider SES due to exceptionally heavy usage. The three-week campaign was therefore eventually extended to 26 days. Beyond the scope of the initial project plan, a simultaneous two-way carrier phase link between OBSPARIS and PTB was also operated in collaboration with NICT during the initial part of the campaign.

Analysis of the data collected was significantly more challenging than for clock comparisons via optical fibre links, mainly due to the fact that the white phase noise and technical disturbances on the link data limit the instability and uncertainty of the optical clock comparisons. An optimized data analysis strategy therefore had to be developed to take these peculiarities into account, enabling final results for clock frequency ratios to be calculated without introducing unnecessary uncertainty. In this way link uncertainties in the low parts in 10^{16} range were finally achieved, which to our knowledge is the best result ever achieved with a telecommunications satellite.

An unexpected, but significant, conclusion from our experiment is that the recently introduced GPS integer precise point positioning (IPPP) technique has a similar performance to broadband TWSTFT in terms of the uncertainty that can be achieved for a given averaging time, but at considerably reduced operational cost and with less effort. 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.

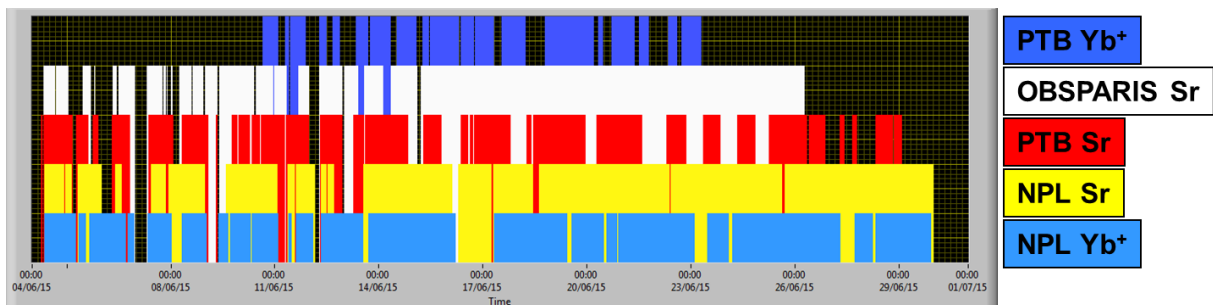


Figure 7. Operational periods for some of the optical clocks involved in the June 2015 measurement campaign.

3.3 Absolute frequency measurements of optical atomic clocks

Absolute frequency measurements of all the operational optical atomic clocks at INRIM, NPL, OBSPARIS and PTB (i.e. the ^{199}Hg , ^{87}Sr , $^{88}\text{Sr}^+$ and $^{171}\text{Yb}^+$ E2 and E3 standards) have been performed during the project lifetime using femtosecond combs. In most cases the measurement uncertainties reached the low parts in 10^{16} level, limited by the uncertainties of the caesium fountain primary frequency standards that were used as local realisations of the SI second in each laboratory.

Where possible, independent absolute frequency measurements have been made at more than one institution to check the consistency. For example, five independent absolute frequency measurements of ^{87}Sr optical lattice clocks have been completed, with agreement being observed between the different clock designs at PTB, OBSPARIS and NPL to the level at which the SI second can be realised, i.e. a few parts in 10^{16} . In the case of the ^{87}Sr system at NPL, this clock was operated and its uncertainty evaluated for the first time during the project.

A second new clock has also come into operation during the project. This is the ^{171}Yb optical lattice clock at INRIM (Figure 8), for which the absolute frequency measurement has so far reached the 10^{-15} level of fractional uncertainty, but with prospects for significant further improvement, since the local caesium fountain primary frequency standard IT-CsF2 has been evaluated to 2×10^{-16} .

The absolute frequency of the ^{199}Hg optical lattice clock at OBSPARIS was measured in the same campaign as the direct optical frequency ratio between the ^{199}Hg and ^{87}Sr lattice clocks discussed in section 3.1. The fractional uncertainty of 3.7×10^{-16} is approximately 20 times lower than that of the previous measurement performed in the same laboratory prior to the start of this project. This improvement is mainly due to reductions in the uncertainties of key systematic frequency shifts of the ^{199}Hg optical clock transition, most notably the shift associated with the lattice laser used to trap the ^{199}Hg atoms.

Several other results of absolute frequency measurements performed during the project lifetime have been obtained from the consortium of another EMRP-funded project, SIB04 - Ion clock, “High accuracy optical clocks with trapped ions”, and have fed into the overall consistency analysis of the clock comparison results (section 3.9). These are an absolute frequency measurement of the $^{88}\text{Sr}^+$ trapped ion optical clock at NPL and absolute frequency measurements of the E2 and E3 optical clock transitions in the $^{171}\text{Yb}^+$ ion at both NPL and PTB. These latter measurements provide a consistency check between the $^{171}\text{Yb}^+$ optical clocks developed independently by the two laboratories, with agreement being observed at the parts in 10^{16} level.

With the exception of the ^{199}Hg standard, all the optical clocks studied have already been accepted as secondary representations of the second, and measurements of the type performed within this project are important for maximising their potential contribution to international timescales prior to a redefinition of the second. Several of the absolute frequency measurements were included in the frequency ratio matrix analysis performed for the CCL-CCTF Frequency Standards Working Group in September 2015 (section 3.9), and thus contributed to the updates to the list of recommended frequency values adopted by the CIPM following that meeting. The results of those absolute frequency measurements that were not available at that time can be expected to be included in the next analysis, which is due to be carried out in the run-up to the next CCTF meeting in June 2017.

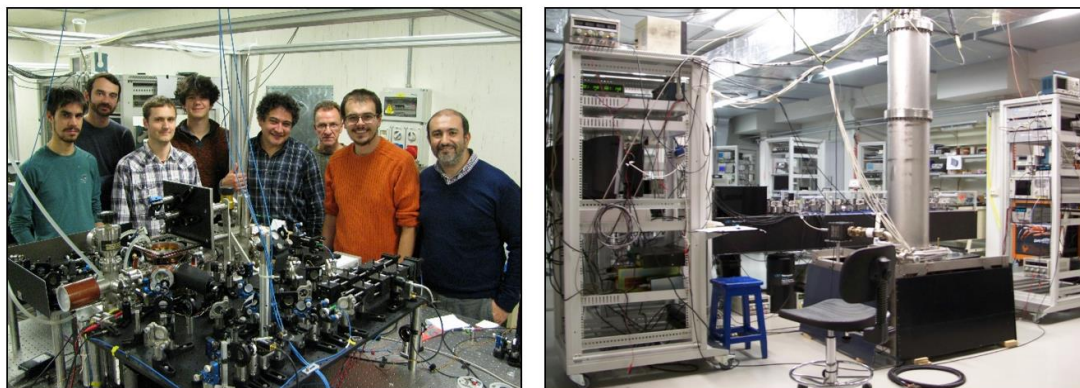


Figure 8. The newly operational ytterbium optical lattice clock at INRIM (left) and the caesium fountain primary frequency standard IT-CsF2 that was used to measure its absolute frequency (right).

3.4 Evaluation of relativistic effects influencing time and frequency comparisons

General relativity predicts that two ideal clocks that move with a relative velocity or that are located in different gravity potentials will in general be observed to run at different frequencies. Similarly, the frequency of a clock with respect to the coordinate time of a particular space-time reference system depends on i) the velocity of the clock in that reference system and ii) the gravitational potential it experiences. Both effects must therefore be taken into account when comparing the frequencies of different optical atomic clocks or considering their future incorporation into international timescales.

Within the project we have described in a relativistic framework three of the most promising techniques for time and frequency transfer. The evaluation of the relativistic effects for broadband two-way satellite time and frequency transfer (TWSTFT) and optical fibre links is described in this section, while the possibilities for performing time transfer with continuously operating optical atomic clocks is discussed in section 3.6. The effects of the gravity potential are considered in section 3.5.

Relativistic effects in broadband TWSTFT

The method used to evaluate and correct for relativistic effects in TWSTFT was based on the theory derived in Petit and Wolf (1994)⁷, which shows that two different effects must be considered: the Sagnac effect and the variation in signal path delays due to satellite motion.

The Sagnac effect arises due to the rotation of the Earth and is dependent on the positions of the satellite and ground stations. Since the satellite orbit is not perfectly geostationary, there is a residual motion of the satellite with a period of one day, meaning that the Sagnac correction also varies with a period of one day. The changes are therefore greatest over 12 hour intervals.

Pulses transmitted simultaneously from two different laboratories arrive at the satellite at slightly different times due to the different path delays. The residual satellite motion means that the satellite is at different positions when the pulses arrive, which leads to an asymmetry in the signal paths in the two directions. This asymmetry varies with time, and again the changes are greatest over 12 hour intervals.

Simulations were carried out to estimate the typical size of these effects for European links. Initial work was based on the Telstar 11N satellite, which is the current satellite used for operational TWSTFT measurements between European NMIs. The ground stations studied were the four NMIs with TWSTFT capability, i.e. INRIM, NPL, OBSPARIS and PTB. These simulations were used to derive requirements on the position and velocity data that would have to be provided by the satellite operator for the broadband TWSTFT optical clock comparison campaign (section 3.2) in order that the relativistic effects could be evaluated with sufficiently low uncertainty for the target clock comparison accuracy to be achieved.

Similar calculations were also performed for the ASTRA 3B satellite that was selected for the broadband TWSTFT experiment, covering both the period of the link test experiment in October 2014 and the optical clock comparison campaign in June 2015. These calculations used position and velocity data obtained from the satellite provider SES. The variations in the Sagnac effect are highest for links involving INRIM and, for the two periods of interest, resulted in average fractional frequency shifts over 12 hour intervals of up to $\pm 9.8 \times 10^{-16}$ for the NPL – INRIM link. The lowest fractional frequency shifts of up to $\pm 3.8 \times 10^{-16}$ over 12 hours were calculated for the NPL – OBSPARIS link. The effect of time-varying path asymmetries was largely eliminated for links between NPL, OBSPARIS and PTB by applying a deliberate time offset in the pulses transmitted by the ground stations so that corresponding pulses from the three laboratories arrived at the satellite at almost the same time. The required time offsets were calculated ahead of the two measurement campaigns based on predicted position and velocity data supplied by SES. In these cases only residual corrections had to be evaluated after the experiment. In the case of links involving INRIM, no time offset was applied to the transmitted pulses and instead the full corrections were applied in post-processing.

In this way the relativistic corrections relevant to the TWSTFT experiment were evaluated to a level of 5×10^{-17} fractional uncertainty, which is sufficiently low that they do not contribute significantly to the final overall uncertainty.

⁷ G. Petit & P. Wolf, "Relativistic theory for picosecond time transfer in the vicinity of the Earth", *Astronomy and Astrophysics* 286, 71–997 (1994)

Relativistic effects relevant to time and frequency transfer over optical fibre links

Optical fibre links are expected to be widely used for time and frequency transfer in the future, at least within continents. To evaluate the relativistic effects relevant for time and frequency transfer using such links, it was necessary to develop methods to account for signal propagation in a medium with a refractive index larger than unity in a relativistic framework.

Within this project, a complete relativistic model for propagation of a signal in an optical fibre was developed by CMI and OBSPARIS⁸, starting with the derivation of equations governing the signal propagation for the general case of any optical fibre in any space-time with a given time coordinate. The equations were then applied to the specific case of an optical fibre located on the Earth's surface. General forms of formulae for one-way and two-way time and frequency transfer were derived. All relativistic effects were included as well as the possibility that fibre conditions might change during the signal transfer (for example due to temperature changes or movements of the fibre due to effects such as Earth tides). Using these equations, relativistic corrections were derived for one-way and two-way time and frequency transfer over optical fibres including all terms exceeding 1 ps for time transfer and 10^{-18} for frequency transfer, which matches the anticipated performance of optical clocks. Most of these effects had never been evaluated in the past.

The magnitudes of these relativistic effects were estimated for typical fibre links. Estimates were also made of the uncertainties in the evaluation of the relativistic corrections, arising from imperfect knowledge of parameters such as the coordinates of the fibre routing. Within the associated researcher mobility grant CMI, the recently-established NPL – OBSPARIS and PTB – OBSPARIS fibre links were studied as specific examples, meaning that the work performed will be of direct relevance to optical clock comparisons performed within the EMPIR-funded 15SIB05 OFTEN project “Optical frequency transfer - a European network”, which runs for three years from June 2016. Guidelines have also been provided on the importance of exact fibre routing for time and frequency transfer via optical fibre links.

3.5 Connection to geodetic models

The strong collaboration the consortium has established between the metrology community and the geodesy community has resulted in the gravity potential being determined with significantly improved accuracy at the sites participating in optical clock comparisons within the project.

For frequency comparisons between optical clocks, the gravity potential difference between the clocks needs to be known, whilst for contributions to international timescales the absolute gravity potential relative to a defined reference surface is also required.

At present, the universally adopted international timescale TAI is “defined in a geocentric reference frame with the SI second as realised on the rotating geoid as the scale unit”. On the other hand, TAI can be considered as a realisation of Terrestrial Time (TT), *i.e.* coordinate time at the Earth's surface. However, TT was re-defined by the International Astronomical Union (IAU) in the year 2000 to avoid explicit mention of the geoid, due to the intricacy and problems associated with the definition, realisation and changes of the geoid. This was done by fixing the rate between Terrestrial Time (TT) and Geocentric Coordinate Time (TCG) through the (defining) constant L_G . For continuity reasons, the numerical value of L_G was chosen such that the scale unit of TT agreed with the SI second on the rotating geoid, and as $L_G = W_0/c^2$ where c is the speed of light in vacuum, this implicitly defines a geopotential value of $W_0 = 62\,636\,856.00 \text{ m}^2\text{s}^{-2}$. Based on the IAU re-definition of TT it is reasonable to choose the latter value for W_0 as the reference potential for the calculation of gravitational redshift corrections associated with clocks contributing to international time scales. In this way the uncertainty of the gravitational redshift correction is given solely by the uncertainty of the determination of the absolute gravity potential at the respective clock location.

For optical clocks with a projected fractional accuracy of 10^{-18} , an accuracy of about $0.1 \text{ m}^2\text{s}^{-2}$ in the gravity potential is required, which corresponds to about 1 cm in height at the Earth's surface.

Determination of the static gravity potential

An initial technical report written by LUH set out the theoretical background for deriving the gravity potential, and made recommendations for the levelling and Global Navigation Satellite Systems (GNSS) observations that needed to be made at the clock sites. Two options were given for deriving the gravity potential. The first

⁸ J. Geršl, P. Delva and P. Wolf, "Relativistic Corrections for Time and Frequency Transfer in Optical Fibres", Metrologia 52, 552–564 (2015)

approach uses the results from gravity field modelling and GNSS positions, and is known in the literature as the geoid/GNSS approach. It can deliver absolute potential values, in the best case giving accuracies of around 2–3 cm. The second approach is based primarily on geometric levelling observations. Geometrical levelling is a differential technique, and thus gives only potential differences. It can provide sub-mm accuracy over short distances, but systematic errors accumulate over larger distances.

Based on the recommendations made in this report, local surveying measurements (Figure 9a) and GNSS measurements were carried out at each clock comparison site (INRIM, NPL, OBSPARIS, PTB and LSM). As a result, height differences within each NMI are known to 1 – 3 mm, depending on the surveying equipment used in each case, and can be used to determine gravity potential differences for local clock comparisons. The surveying results were collected by LUH and unified in a single dataset based on a consideration of the different national height systems. Based on the GNSS and surveying results, together with a global and a preliminary regional geoid model, preliminary absolute gravity potentials for each site were derived.

In order to obtain the best possible final values for the gravitational redshifts of the optical clocks, a new campaign of gravity measurements was undertaken, based on at least one absolute gravity observation with the LUH FG5X-220 instrument at each clock site and between 35 and 122 relative gravity observations around each site (Figure 9b). The purpose of these new gravity observations was threefold: i) to perform spot consistency checks of the largely historic gravity database, ii) to improve coverage by adding new observations in areas void of gravity data, and iii) to serve future geodynamic and metrological purposes. These new gravity measurements were integrated into the existing European gravity database and used in combination with topographic information and a global geopotential model to conduct a complete recomputation of the quasi-geoid for the entire European area, a new model denoted as the European Gravimetric (Quasi)Geoid (EGG2015). Apart from the inclusion of the new gravity measurements, the main difference between EGG2015 and the previous EGG2008 quasi-geoid model is that a newer global geopotential model based on the GOCE satellite mission was used in the computation.

The accuracy of the EGG2015 quasi-geoid model has been elaborated following the approach in Denker (2013)⁹, yielding a standard deviation of about 2.0 cm for the absolute quasi-geoid heights in the best case scenario, i.e. when sufficient terrestrial data is available around the sites of interest. This is a small improvement compared to EGG2008 and stems mainly from the improved accuracy of the GOCE global geopotential model compared to the previously used GRACE-based model. For the NMI sites, the gravity data situation is reasonably good in all cases, and the error estimate above can be used in the estimation of gravity potential values. The largest differences in the quasi-geoid heights are found for the sites in mountainous regions (LSM) and where the previously existing gravity coverage was less dense (LSM and INRIM). This is due partly to the significant number of new gravity observations made within the project, but also to the more detailed data screening performed, where several old (mainly French) gravity points with incorrect positions were identified. For gravity potential differences over distances of more than 300 km (i.e. between different NMIs), the error correlations between the quasi-geoid values are close to zero.

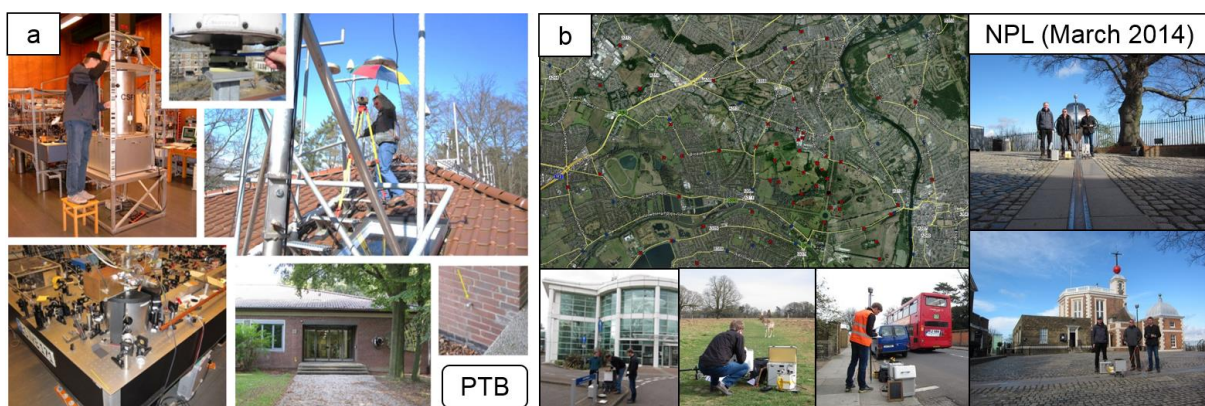


Figure 9. (a) Surveying measurements performed at PTB. Similar measurements were carried out at INRIM, NPL, OBSPARIS and LSM. (b) Gravity measurement campaign performed by LUH at and around the NPL site. Similar measurements were carried out at and around the INRIM, OBSPARIS, PTB and LSM sites.

⁹ Denker, H. (2013) Regional gravity field modeling: Theory and practical results. In: Xu, G. (ed.), Sciences of Geodesy – II, Chapter 5, DOI: 10.1007/978-3-642-28000-9_5, pp 185-291, Springer-Verlag Berlin Heidelberg

Time-variable gravity potential signals

Besides the predominant static part of the gravity potential, temporal variations must also be considered. Within this project a first comprehensive study has been performed of the magnitudes and dominant time periods of time-variable gravity potential effects relevant to optical clock comparisons at the 10^{-18} level.

The dominant components of the time-variable potential come from solid Earth and ocean tides, with peak-to-peak ranges of roughly $5 \text{ m}^2\text{s}^{-2}$ and up to $0.6 \text{ m}^2\text{s}^{-2}$ respectively. The time series of the gravity potential due to these effects was modelled and calculated on a 1-hourly basis for the year 2014 at the clock comparison sites involved in this project, i.e. INRIM, NPL, OBSPARIS, PTB and collaborator LSM. The amplitudes of the time-variable components are relevant for contributions to international timescales. For clock comparisons over short distances the effects will largely be common mode and hence almost cancel out, but over longer (intercontinental) distances they may reach up to twice the amplitude of the variation at a single point. Other time-varying effects on the Earth's gravity potential with maximum amplitude ranges of about $0.2 \text{ m}^2\text{s}^{-2}$ have also been studied, including other tidal effects from polar motion as well as non-tidal mass redistributions in the atmosphere, the oceans and the continental water storage. These effects can also affect clock comparisons at the 10^{-18} level.

Potential application of optical clocks in relativistic geodesy

A post-Newtonian framework including nonlinear relativistic effects has been used to study the idea of a worldwide optical clock network for measuring the space-time geometry around the Earth. This approach, based on clock measurements, is an alternative to classical geodesy methods. Following an extensive review of past work on relativistic geodesy, all the theoretical tools necessary for relativistic geodesy were presented and applied for the case of a stationary and axially symmetric parameterized Post-Newtonian metric. The special case of a stationary clock on the surface of the Earth was studied. Some interesting conclusions concerning post-Newtonian corrections are that (i) differences between the chronometric geoid and the Newtonian geoid are of order 2 mm; (ii) post-Newtonian corrections for gravimeters are above or just at the level of current accuracy of the best absolute gravimeters, which is about $1 \mu\text{Gal}$ ($1 \text{ Gal} = 10^{-2} \text{ ms}^{-2}$); (iii) post-Newtonian corrections for gradiometers are below current accuracy, a few μE ($1 \text{ E} = 10^{-9} \text{ s}^{-2}$), but could be measurable by integrating for a long time with a satellite mission.

An evaluation was then made of the potential contribution of clock networks in determining the geopotential at high spatial resolution ($\approx 10 \text{ km}$). Synthetic calculations were performed in which the potential was reconstructed from gravity data with and without clock data. Two mountainous terrains in France, the Massif Central and the Alps, were chosen as test cases. These regions are interesting because the gravitational field strength varies greatly from place to place over short distances due to the complex topography. The synthetic test methodology used consists of the generation of synthetic gravity and potential data, then the estimation of the potential from these data using least-squares collocation and assessment of the contribution of the clocks. We have shown that adding only a few clock data points in zones with poor gravity information (less than 1 percent of the gravity data) reduces the bias and improves the standard deviation of the determined geoid. For both regions, the standard deviation was improved by about a factor of 2 and the bias by about a factor of 10.

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

Up until now, by far the most commonly transported atomic clocks have been portable commercial caesium clocks with stabilities of order a few parts in 10^{14} over one day. These are occasionally used for clock trips between laboratories for the purpose of time transfer. Typical time transfer uncertainties that can be achieved in this way are a few nanoseconds over periods of one day. Future portable optical clocks with much higher stabilities offer prospects for orders of magnitude improvements in time transfer capability, as long as the relativistic effects relevant to the transport of the clock can be corrected with sufficiently high accuracy.

Within this project we used a known approach to evaluate the relativistic effects, using realistic trajectories along which continuously operating optical clocks might be transported. The relativistic effects are related to the varying gravity potential along the clock trajectory, the velocity of the transported clock within the Earth-fixed reference system and the Sagnac term. Simulations were performed for three different clock

trajectories. Route 1 involved land and sea transport between NPL and PTB, route 2 was from PTB to OBSPARIS and route 3 was from INRIM to collaborator LSM. The second and third trajectories involved only transport by land. Independent simulations were performed by NPL and LUH, with route 1 being studied using different simulation software to routes 2 and 3. However both studies led to similar conclusions.

The results show that, depending on the speed of transportation, the total relativistic effect can be several nanoseconds, and must therefore be taken into account in real clock transport experiments. Depending on the quality of the navigation system used, the uncertainty of the corrections is at the level of 0.01–1 ps.

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

Although the main focus of this project was on the future realisation of international timescales, we also aimed to demonstrate the impact that optical clocks could have on the field of geodesy, by showing that they can be used to measure gravity potential differences over medium–long baselines. In contrast to other instruments used for gravity measurements, optical clocks are directly sensitive to the gravity potential, which determines their gravitational redshift. Within this project we carried out a proof-of-principle experiment in which the gravitational redshift of an optical clock was used to measure the gravity potential difference between two well-defined locations.

The concept of the experiment was to compare two optical clocks, as illustrated schematically in Figure 10. The first optical clock was the ^{171}Yb optical lattice clock at INRIM in Turin, Italy. The second was the transportable ^{87}Sr optical lattice clock from PTB, which in February 2016 was taken to collaborator LSM in the Fréjus tunnel, close to the France-Italy border. The frequency comparison between the two clocks was performed using a 150 km coherent optical fibre link between the two laboratories. Two optical frequency combs were also required for the frequency ratio measurement between the two optical clocks, because the transmission window of the optical fibre link is at $1.5\ \mu\text{m}$. Since no frequency comb was available at LSM, a transportable optical frequency comb from NPL was used to link the frequency of the clock laser for the transportable lattice clock to that of a $1.5\ \mu\text{m}$ transfer laser. Because the two clocks are based on different transitions, the proper frequency ratio between them must also be determined by subsequently transferring the PTB transportable lattice clock to INRIM.

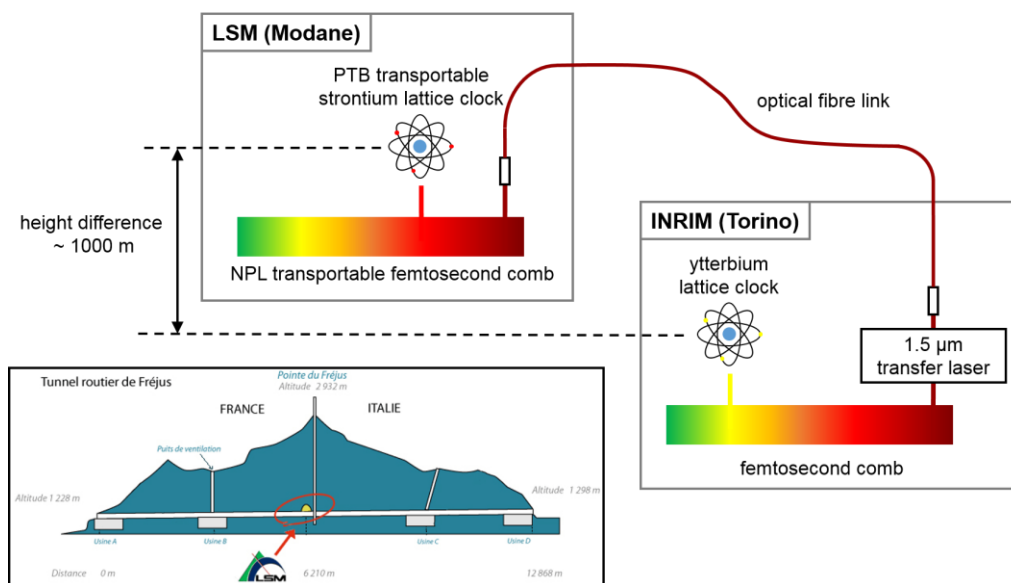


Figure 10. Schematic diagram showing the experimental configuration for the proof-of-principle clock-based geodesy experiment.

The INRIM-LSM test-bed offers a large gravity potential difference, with a height difference of approximately 1000 m between the two sites. The expected gravitational redshift is therefore about 10^{-13} . The gravity potential difference between the two sites was determined using standard geodetic methods in 2015 by LUH in collaboration with INRIM and the collaborator Politecnico di Torino, giving a value that can be compared with the one obtained using the clocks. The LSM laboratory is in an interesting location to make such measurements from a geodetic point of view: firstly it is located under a mountain in the middle of the Fréjus tunnel, and secondly the area exhibits long-term subsidence meaning that the gravity potential will change over time.

The environmental conditions at LSM are very different from those of a typical optical clock laboratory in a national metrology institute. In particular, the underground laboratory (Figure 11) is subject to relatively large temperature fluctuations and high background acoustic noise levels. Operating the transportable strontium optical lattice clock under these conditions proved to be technically very challenging, but was eventually achieved for a few hours on two days in the middle of March 2016. However, this period of successful operation coincided with a failure of one of the lasers for the ^{171}Yb lattice clock at INRIM, meaning that a direct comparison of the two optical clocks was not possible. Instead, the frequency of the transportable strontium lattice clock was measured against the INRIM caesium fountain primary frequency standard, which was running throughout the entire campaign. By using an INRIM hydrogen maser as a flywheel to bridge gaps in the optical clock operation, an uncertainty at the 10^{-15} level was achieved for the remote frequency comparison. The gravity potential difference deduced from this remote clock comparison is consistent with the value obtained using conventional geodetic methods.

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, and there are excellent prospects for improving the accuracy achieved in our initial experiment by orders of magnitude as the reliability and robustness of transportable optical clocks improves.

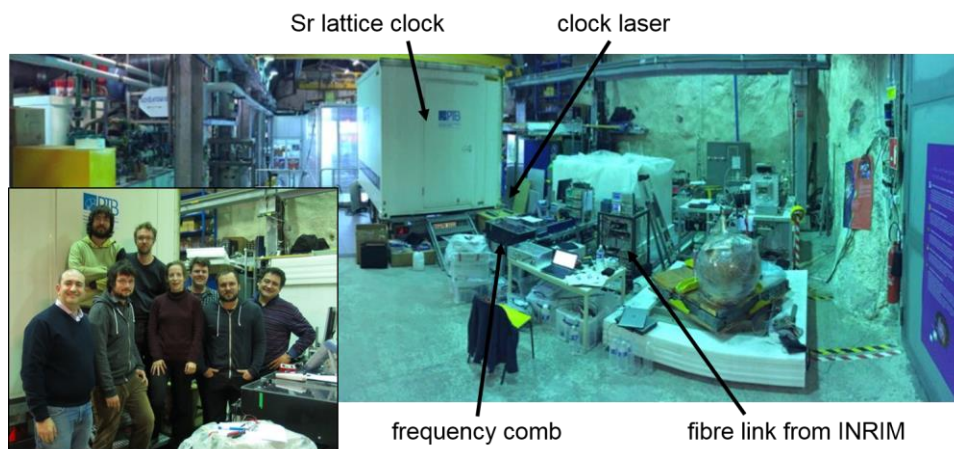


Figure 11. The experimental setup in the underground laboratory at LSM. Inset: the optical clock and femtosecond comb teams from PTB and NPL, with colleagues from INRIM.

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

The clock comparison programme carried out within this project has led to a set of frequency ratio measurements between the high accuracy optical atomic clocks being developed within European NMIs, as well as a comprehensive set of absolute frequency measurements with uncertainties at the limit set by caesium primary frequency standards. This frequency ratio measurement matrix is over-determined, in the sense that it is possible to deduce some frequency ratios from the results of several different experiments. For example, the optical frequency ratio between the $^{171}\text{Yb}^+$ E3 and ^{87}Sr optical clock transitions has been measured directly by both NPL and PTB, but it can also be determined indirectly by combining the results of absolute frequency measurements of these transitions made in the two laboratories. These multiple routes to deriving the optical frequency ratio mean that all the measurements must be considered when deriving a “best” value for the ratio.

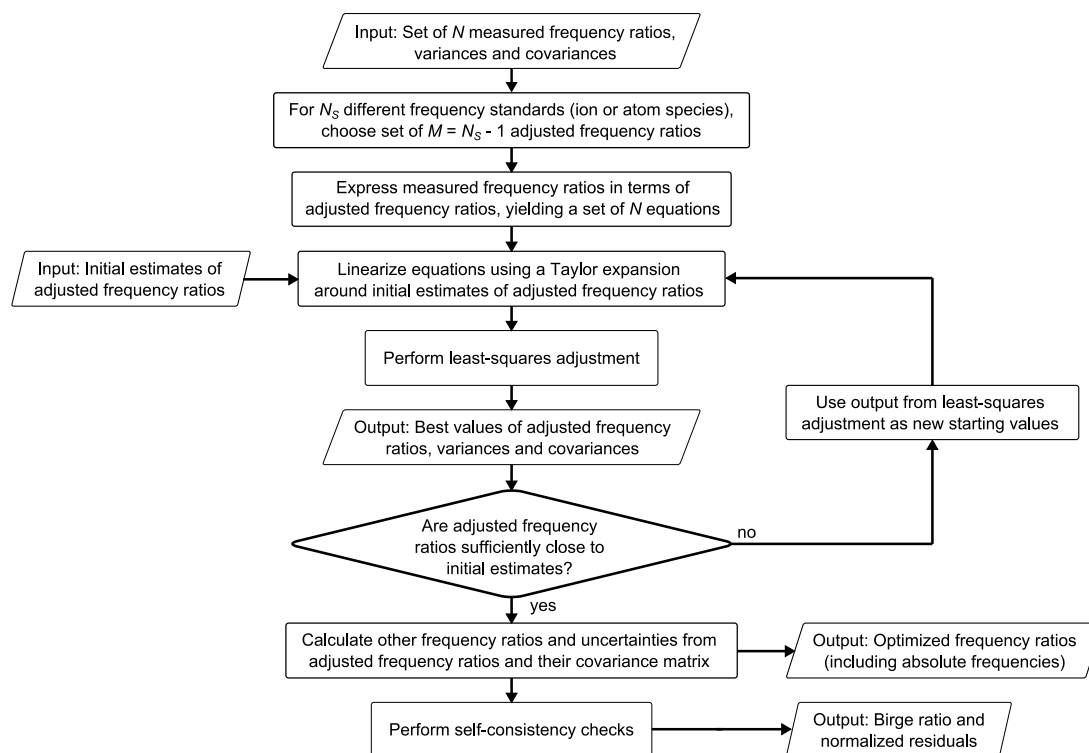


Figure 12. Least-squares analysis procedure developed to derive a self-consistent set of optimized frequency ratio values from an over-determined set of clock comparison data such as the one generated within this project.

Within this project a method has been developed for handling over-determined sets of clock comparison data in order to derive optimised values for the frequency ratios between each contributing standard¹⁰. This is a least-squares adjustment procedure (Figure 12), based on the approach used by CODATA to derive a self-consistent set of values for the fundamental physical constants.

The input data to the least-squares adjustment are a set of N frequency ratio measurements between clocks based on N_s different reference transitions, together with the variances and covariances of these frequency ratio measurements. All input data is treated in a similar way, with absolute frequency measurements simply being a special case of frequency ratios involving the caesium primary standard. The measured frequency ratios are expressed as a function of one or more of a set of $M = N_s - 1$ adjusted frequency ratios, yielding a set of N equations that are, in general, nonlinear. It is the values of these adjusted frequency ratios that are optimised in the least-squares adjustment.

The equations relating the measured frequency ratios to the adjusted frequency ratios are linearized prior to the least-squares adjustment by using a Taylor expansion around initial estimates of the adjusted frequency ratios. This enables linear matrix methods to be applied to yield best estimates for the values of the adjusted frequency ratios, their variances and covariances. Because a linear approximation has been made, this solution will not be exact. However, the improved values of the adjusted frequency ratios obtained from the least-squares adjustment can be used as starting values for a new linear approximation and a second least-squares adjustment performed. This process is repeated until the new values of the adjusted frequency ratios obtained from the least-squares adjustment are sufficiently close to the values obtained in the previous iteration. The number of iterations required to satisfy this condition depends on how close the initial estimates are to the adjusted frequency ratios emerging from the final iteration. Once convergence has been obtained, any other frequency ratio of interest (and its uncertainty) can then be calculated from the adjusted frequency ratios and their covariance matrix. Self-consistency checks are also performed on the body of data to identify any issues with the uncertainty evaluations for each individual clock comparison.

¹⁰ H. S. Margolis and P. Gill, "Least-squares analysis of clock frequency comparison data to deduce optimized frequency and frequency ratio values", *Metrologia* 52, 628–634 (2015).

The software algorithms developed within this project and implemented in Matlab were shown to reproduce the frequency values recommended by the International Committee for Weights and Measures (CIPM) in 2013, when using the same input data that the Frequency Standards Working Group (WGFS) of the Consultative Committee for Time and Frequency (CCTF) and the Consultative Committee for Length (CCL) used to derive those values. The uncertainties determined from our least-squares analysis are, however, smaller than those assigned to the CIPM values. The reason for this is that measurements of a particular frequency ratio have usually only been made by a few independent research groups, or in some cases only one. This leads the WGFS to take a conservative approach to uncertainty estimation, typically multiplying the relative standard uncertainty of the weighted mean of a set of frequency values by a factor of two or three.

This project has also identified the key issues encountered in assessing over-determined sets of frequency comparison data. Firstly, it is necessary to identify and critically review all possible input data, with particular attention being paid to the standard uncertainty associated with each measurement. Secondly, the correlations between the input data must be considered carefully, since neglecting such correlations results in certain measurements being given too much weight in the least-squares adjustment, resulting in biased frequency values and underestimated uncertainties. However, the information reported in the literature is in many cases insufficient to calculate the correlation coefficients, meaning that additional information must be sought from the groups that carried out the measurements in order that each input datum is given the appropriate weight in the least-squares adjustment. Finally the extent to which each input datum contributes to the determination of the adjusted frequency ratios must be investigated, as well as the effects of omitting inconsistent or inconsequential data as may be deemed appropriate.

Our work has thus led to a new tool that can be used not only to analyse the frequency ratio measurement matrix derived from the optical clock comparison programme carried out within this project, but also to analyse larger data sets that incorporate the results of clock comparison experiments performed by other research groups around the world. Such an analysis is described in the following section.

3.9 Optimised values for the frequency of each optical clock transition

As a first step towards a redefinition of the SI second, seven optical clocks ($^{27}\text{Al}^+$, $^{199}\text{Hg}^+$, $^{171}\text{Yb}^+$ E2, $^{171}\text{Yb}^+$ E3, ^{171}Yb , $^{88}\text{Sr}^+$ and ^{87}Sr) can already be used as secondary representations of the second, with recommended frequencies and uncertainties assigned by the WGFS. These recommended frequency values and uncertainties are periodically reviewed, updated and published on the website of the International Bureau of Weights and Measures (BIPM) as part of a longer list of recommended frequency values¹¹. In this review process the WGFS considers the complete set of clock comparison data available worldwide.

Prior to 2015, almost all the data considered by the WGFS came from absolute frequency measurements made relative either to caesium fountain primary frequency standards or International Atomic Time (TAI). The sole exception was a direct measurement of the optical frequency ratio between the optical clock transitions in $^{27}\text{Al}^+$ and $^{199}\text{Hg}^+$ at NIST, which was used to derive a second absolute frequency value for $^{27}\text{Al}^+$ with much lower uncertainty than the directly measured frequency.

At the most recent meeting of the WGFS, held in September 2015, the situation was rather different. Not only were a number of new absolute frequency measurements submitted to the group for consideration, five new direct optical frequency ratio measurements were also reported. The complete body of data was thus over-determined, as indicated in Figure 13. For example, the frequency of the ^{171}Yb , ^{87}Sr , ^{199}Hg and $^{40}\text{Ca}^+$ (being studied outside of this consortium) standards were coupled by direct optical frequency ratio measurements, as were the frequencies of the E2 and E3 transitions in $^{171}\text{Yb}^+$.

The analysis techniques described in section 3.8 were designed to deal with exactly this type of situation, allowing a self-consistent set of optimised frequency ratio values between high accuracy frequency standards (both optical and microwave) to be derived, based on an over-determined data set resulting from a series of clock comparison experiments. As a consequence, the WGFS used our software algorithms in preparing an updated list of recommended frequency values in September 2015, enabling full benefit to be derived from the experimental data available at that time.

¹¹ <http://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html>

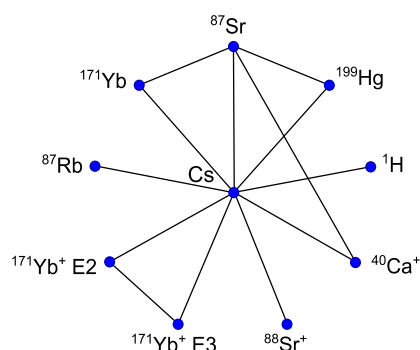


Figure 13. New frequency ratio measurements submitted for consideration by the WGFS in September 2015. Most were absolute frequency measurements, i.e. frequency ratios involving the caesium primary standard. However, four optical frequency ratios had also been measured directly (in one case by two independent research groups), meaning that the complete dataset was overdetermined. Out of a total of 17 absolute frequency measurements and five direct optical frequency ratio measurements, 9 absolute frequency measurements and one optical frequency ratio measurement were performed by the European NMI's involved in this project. Most of these were performed either in this project or the related project SIB04 – Ion clock, “High accuracy optical clocks with trapped ions”.

Figure 14 shows how the optimised frequency values obtained for the optical secondary representations of the second change when this new data is included in the least-squares analysis¹². Correlations between the input data were assumed to be negligible, with the exception of recent measurements involving the $^{171}\text{Yb}^+$ standards at NPL. In this case the absolute frequency measurements of the E2 and E3 transitions were performed during the same campaign as the measurement of the direct optical frequency ratio between them. This led to non-negligible correlations between the three values, for which the correlation coefficients had been calculated.

It is clear from Figure 14 that including the new data in the least-squares analysis leads to significant shifts in the optimised frequency values, demonstrating that the conservative approach to uncertainty estimation employed by the WGFS is prudent. It is emphasised that the uncertainties of the new optimised frequency values shown in Figure 14 are the uncertainties emerging from the least-squares adjustment, rather than the more conservative uncertainties finally assigned by the WGFS after extensive discussion amongst the members of the committee.

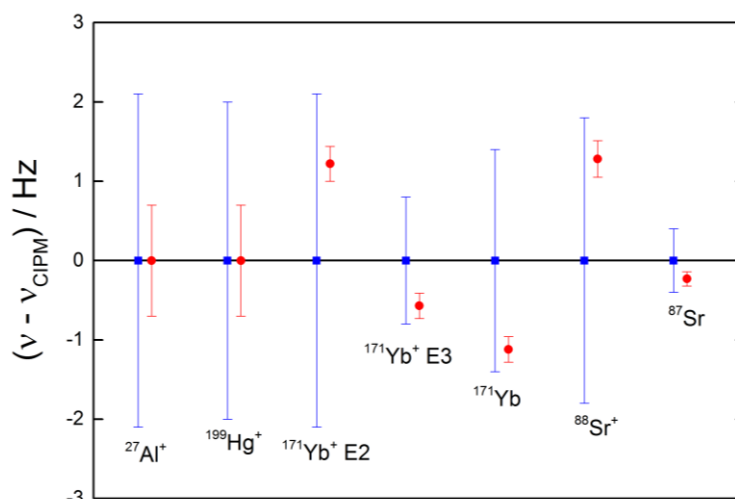


Figure 14. Optimised frequency values obtained from our analysis software for the seven secondary optical secondary representations of the second, calculated using all clock comparison data submitted to the WGFS in September 2015 (red circles). The uncertainties shown for the new results are those calculated in the least-squares adjustment procedure, rather than those finally assigned by the WGFS. The 2013 CIPM recommended frequency values and uncertainties (blue squares) are shown for comparison.

¹² H. S. Margolis and P. Gill, “Determination of optimized frequency and frequency ratio values from over-determined sets of clock comparison data”, *Journal of Physics: Conference Series* 723, 012060 (2016)

The updated recommended frequency values and uncertainties were approved by the CIPM in October 2015 and have subsequently been published on the BIPM website.

The analysis methods developed within this project will become increasingly important as the number of direct optical frequency ratio measurements increases, and will enable valuable information to be derived about the relative performance of different candidates for an optical redefinition of the second. The fact that correlations are taken into account in the least-squares adjustment is likely to become increasingly important in future, as more high accuracy clocks are compared in measurement campaigns involving multiple institutions.

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

Timescales must be realised without interruption for them to provide a continuous coordinate system for measuring the position of events in time. If optical clocks are to make regular contributions, either to the international timescales TAI and UTC or to local timescales realised within individual NMIs, 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 timescale.

Compared to caesium fountain primary frequency standards, which routinely operate for many days with minimal user intervention in a number of NMIs around the world, the increased technological challenges and complexity of optical clocks currently limit the periods for which continuous operation can be achieved. Significant improvements in this respect have recently been achieved within this project, with optical clock up-times of 60–90 % being achieved during our 26-day clock comparison campaign in June 2015. However it is still necessary to bridge gaps with a local flywheel frequency reference in order to obtain data that can be used for steering corrections to TAI, and this flywheel results in an additional source of uncertainty.

It has been shown within this project that sufficiently stable hydrogen masers or optical cavities can be used as flywheel oscillators to bridge surprisingly long gaps in optical clock data without significantly degrading clock comparison uncertainties¹³. In general, the instability of the flywheel oscillator means that there will be a difference between its frequency averaged over a period T_{opt} during which it is being compared with an optical clock and an extended period T_{ext} . This difference in average frequency is unknown to within some uncertainty u_{ext} , which can be calculated as long as the flywheel's spectrum of frequency fluctuations is known. 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.

When considering the use of optical clocks to provide steering corrections to TAI and UTC, another uncertainty contribution results from the performance of the frequency transfer techniques available. Whilst the techniques currently used for clock comparisons between NMIs offer stabilities that are satisfactory for TAI steering contributions using caesium fountain primary frequency standards, the performance of these operational techniques would significantly degrade the uncertainties that otherwise could be achievable with optical clocks.

This impact has been considered within our project, along with the gains to be made by using alternative techniques. On a continental scale, it is clear that fibre links are more promising than satellite-based techniques, and would allow optical clocks to be used for TAI steering with negligible degradation of uncertainty. On an intercontinental scale, enhanced satellite-based concepts such as ACES will be required to reduce the link uncertainties. For ACES, its on-board hydrogen maser and cold caesium clock PHARAO can be regarded as flywheel oscillators in space, orbiting around the earth. Other important contributions of our work have been the development of novel or enhanced tools for data analysis and statistical description of the data, such as gap-tolerant algorithms for modified Allan deviation estimation and optimal noise-suppression weighted averaging¹⁴.

¹³ C. Grebing et al., "Realization of a timescale with an accurate optical lattice clock", *Optica* 3, 563–569 (2016).

¹⁴ E. Benkler, C. Lisdat and U. Sterr, "On the relation between uncertainties of weighted frequency averages and the various types of Allan deviations", *Metrologia* 52, 565–574 (2015).

An additional aspect of the work undertaken was to investigate the best way of scheduling contributions from optical clocks in order to achieve the best stability of an international timescale. Assuming that the long-term behaviour of the flywheel used can be modelled by a linear drift, as in the case of an active hydrogen maser, it was concluded that i) an optical clock availability of at least 35% would be required during the period of interest, to avoid the dead times degrading the estimate of the frequency uncertainty, ii) measurements should ideally be symmetrically placed with respect to the estimation epoch, and iii) flywheel calibrations should be performed as close as possible to the estimation epoch.

3.11 Key results and conclusions

In summary, the key results and conclusions of the research undertaken within this project are as follows:

- We have carried out a comprehensive set of local frequency comparisons between high accuracy optical clocks in European NMIs, including both direct optical frequency ratio measurements and absolute frequency measurements relative to primary caesium standards. Most of the optical frequency ratios had never been measured before, while the uncertainties of the absolute frequency measurements are reduced compared to previous measurements.
- Using a broadband version of two-way satellite time and frequency transfer (TWSTFT) we have carried out by far the most extensive remote optical clock comparison campaign ever performed, achieving link uncertainties in the low parts in 10^{16} range, approximately an order of magnitude better than achieved using the standard TWSTFT currently used to compare microwave clocks for the computation of TAI and UTC.
- The recently introduced GPS integer precise point positioning (IPPP) technique has been shown to have similar performance to broadband TWSTFT, but with the significant advantage that it is a considerably cheaper and more robust technique that can readily be put into regular operation.
- We have demonstrated the first functional transportable optical clock worldwide, and this has achieved a better performance than any other mobile frequency standard, both in terms of instability and uncertainty.
- Relativistic effects affecting optical clock comparisons have been evaluated at the 10^{-18} level of accuracy, compatible with the projected uncertainties of the clocks. These effects include the gravitational redshift of the clock transition frequencies, which required an improved evaluation of the gravity potential at the European NMIs.
- A new European quasi-geoid model has been computed, incorporating the new gravity measurements carried out at and around the NMI sites. This has unified the description of the geopotential for European NMIs and will also benefit the geodesy community.
- New methods and procedures have been developed for analysing over-determined sets of clock frequency comparison data such as that generated within this project. These methods were used by the CCL-CCTF Frequency Standards Working Group in September 2015 in updating the list of CIPM recommended frequency values.
- We have carried out a proof-of-principle experiment in which an optical clock was used to measure the gravity potential difference between two remote locations, demonstrating the future benefits that measurements of this type could bring to the geodesy community.

These achievements go well beyond what could have been achieved by a single institution, with the comparison of optical clocks developed by different NMIs being an intrinsically collaborative activity that is key to assessing how well the clocks perform. We have harnessed the collective efforts of European NMIs to carry out a coordinated and extensive programme of optical clock comparisons, leading the way in verifying their estimated uncertainty budgets. Future comparisons of this type, both within Europe and beyond, will be essential as the uncertainties of the optical clocks continue to improve.

4 Actual and potential impact

4.1 Impact on the future SI

The most direct impact of this project has been 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).

Improved frequency values for secondary representations of the second

Several of the absolute frequency measurements and optical frequency ratio measurements performed within this project were submitted to the WGFS for consideration at their meeting in September 2015, and thus contributed to the updates to the list of recommended frequency values adopted by the CIPM following that meeting, including the values for optical secondary representations of the second. The least-squares analysis methods and software developed as part of our research also played an important part in this update, and proved very timely since they enabled the WGFS to deal with a situation they were facing for the first time: an over-determined set of clock frequency comparison data including both absolute frequency measurements and a number of high accuracy direct optical frequency ratio measurements. Our research enabled the group to make full use of the available data in order to derive optimised frequency values and uncertainties for each standard.

Results of absolute frequency measurements and optical frequency ratios that were not available in September 2015 will be submitted for consideration in the next analysis performed by the WGFS, which is due to be carried out in the run-up to the next CCTF meeting in June 2017.

Improved stability of international timescales

As a result of our work, together with measurements made in other NMIs around the world, the uncertainties associated with the recommended frequency values for three out of the seven optical secondary representations of the second (^{87}Sr and the E2 and E3 transitions in $^{171}\text{Yb}^+$) are now at the limit set by the accuracy with which the current definition of the second can be realised (5 – 6 parts in 10^{16}). In conjunction with the very high up-times we have demonstrated for the optical clocks during measurement campaigns performed within the project, this opens the way for optical clocks to be used on a regular basis to provide steering corrections to TAI, along with caesium primary standards. Increasing the number of high accuracy clocks used to determine the steering corrections will improve the stability of international timescales, and thus benefits end users even before a redefinition of the second.

Independently verified optical clock performance

In June 2015 this project consortium carried out by far the most extensive remote optical clock comparison campaign that has ever been performed, involving optical clocks in four different European NMIs (INRIM, LNE/OBSPARIS, NPL and PTB), and achieving link uncertainties in the low parts in 10^{16} range. That such a large-scale remote comparison has been successfully carried out by a European consortium demonstrates the strength of European metrology in both optical clock and link research. The results provide detailed information about the consistency of optical clocks within Europe, and 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 limitations of existing optical clock systems have been characterised, and specific improvements identified. This knowledge will inform future work targeted at reaching even lower uncertainties, such as that being pursued in the new EMPIR-funded 15SIB03 OC18 project, "Optical clocks with 1×10^{-18} uncertainty" which started in May 2016.

The verification of optical clock performance levels will allow the international community to make better informed decisions regarding a future redefinition of the second. It will also 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.

Techniques for intercontinental clock comparisons

The best optical atomic clocks have already reached estimated systematic uncertainties in the low parts in 10^{18} range, and continued effort is underway to improve their stability and accuracy. On a continental scale,

optical fibre links are clearly the way to improve clock comparison uncertainties to a compatible level, and within Europe optical clock comparisons using this approach are planned within the EMPIR-funded 15SIB05 OFTEN project that runs from June 2016 – May 2019. However, at present there seems no realistic prospect of employing optical fibre links for clock comparisons on a worldwide scale. It is therefore of interest to pursue alternatives, and within this project we have obtained important results that pave the way for future intercontinental clock comparison experiments.

Firstly, an unexpected result from our large-scale clock comparison campaign performed in June 2015 is that GPS-IPPP yields a performance that is comparable to or even better than broadband TWSTFT, but at considerably reduced operational cost and with less effort. 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. GPS time and frequency transfer links are already in place between NMIs, and we can therefore expect to see intercontinental optical clock comparisons performed using this technique in the next few years. The experience and data analysis strategies developed as a result of this clock comparison campaign are expected to be of significant benefit in other projects that aim to push the performance of satellite-based time and frequency transfer techniques to new levels, such as the Atomic Clock Ensemble in Space (ACES) mission of the European Space Agency.

Secondly, we have developed and demonstrated the first functional transportable optical clock worldwide. The performance achieved is better than for any other mobile frequency standard so far reported, both in terms of instability and uncertainty. This work thus opens up prospects for using transportable optical clocks for future intercontinental comparisons.

The international metrology community has been made aware of both these developments through engagement with the CCTF Working Group on Two-Way Satellite Time and Frequency Transfer (WG TWSTFT) and the CCTF Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WGATFT).

Finally, we have demonstrated that clocks on different continents can be compared without any direct link between them, by measuring the same optical frequency ratio in the two continents. The $^{199}\text{Hg}/^{87}\text{Sr}$ optical frequency ratio measured at OBSPARIS is in good agreement with an independent measurement performed at RIKEN in Japan, and is the first intercontinental agreement between optical frequency ratio measurements with an accuracy beyond that of the realization of the SI second. Whilst such a measurement does not provide completely definitive proof that the frequencies of the two ^{199}Hg clocks or the frequencies of the two ^{87}Sr optical clocks are the same, it does set stringent constraints on which systematic frequency shifts might not have been properly accounted for. Future measurements of this type, involving similar pairs of optical clocks developed independently in different continents, are likely to play an increasingly important role in demonstrating international equivalence of the new generation of clocks.

Unified description of the geopotential for European NMIs

As a result of measurements and calculations performed within this project, the gravity potential has been determined with significantly improved accuracy at the European NMIs currently operating high accuracy optical atomic clocks (INRIM, LNE/OBSPARIS, NPL and PTB). Collaboration between the metrology community and experts from the geodesy community has led to a common description of the geopotential for all NMIs concerned, and has led to a unification of time and frequency metrology in Europe in terms of the gravitational redshift of the clock frequencies. The gravity potential values have been used in optical clock comparison experiments carried out outside the scope of the project¹⁵, as well as those performed within it.

The gravity measurement campaigns undertaken within the project have also already benefitted other metrology experiments such as the cold atom gravimeter and watt balance experiments at OBSPARIS.

Roadmap towards a future redefinition of the SI second

The results and capabilities demonstrated within the project have also influenced the international roadmap towards a redefinition of the SI second, which has recently been prepared by the CCTF Working Group on Strategic Planning (WGSP).

¹⁵ C. Lisdat *et al.*, “A clock network for geodesy and fundamental science”, arXiv:1511.07735 (2015).

4.2 Capacity building and training

Capacity building

Our project consortium included not only those European NMIs that have been working on optical clocks for many years (LNE/OBSPARIS, NPL and PTB), but also those NMIs that started activities in this area more recently (INRIM and VTT). This has enabled them to develop their capabilities more rapidly than would have been possible if they were working alone.

During this project one new European optical clock has been completed and characterised: the ^{171}Yb optical lattice clock at INRIM. This provides Italy with an optical standard that can be disseminated over optical fibre links to other scientific users around the country, such as the European Laboratory for Nonlinear Spectroscopy (LENS) and the Institute of Astrophysics and Radioastronomy. It is the first ^{171}Yb optical lattice clock in Europe, and opens up a route to comparing optical clocks in three different continents via optical frequency ratio measurements between ^{171}Yb and ^{87}Sr optical lattice clocks, since such measurements can now be carried out in Europe, Japan and the USA. Significant progress has also been made on the development of a transportable strontium ion clock at VTT in Finland.

CMI has benefitted from the award of a researcher mobility grant who has carried out guestworking research at OBSPARIS, enabling CMI to extend their experience in general relativity to calculations relevant to high accuracy time and frequency metrology.

NPL also hosted a guest worker from IMBIH (Bosnia and Herzegovina) for a 15-week secondment, providing IMBIH with the opportunity to gain experience related to the operation and development of a national timescale.

More widely, the availability of optical clocks with verified performance levels will support developments being undertaken within national programmes. For example, the optical clocks and frequency comparison capabilities at NPL will be used to characterise portable and robust clocks being developed within the UK quantum technologies programme¹⁶.

Training

European NMIs involved in this project have benefitted greatly from the involvement of geodesy experts from the LUH, with knowledge and experience on geodetic methods and procedures being shared during the 6-monthly project review meetings and during the gravity measurement campaigns performed at INRIM, NPL, OBSPARIS, PTB and collaborator LSM.

A highly successful summer school on optical clocks was held at INRIM from 29th June – 3rd July 2015, and was organised in cooperation with the Marie-Curie Initial Training Network (ITN) on Future Atomic Clock Technology (FACT), which is coordinated by the University of Birmingham, UK. This covered a comprehensive range of topics relating to optical frequency standards and metrology, and was attended by invited speakers from the metrology community outside Europe (USA, Canada, Japan and Australia) as well as by invited speakers from outside the metrology community. Other lectures were given by members of the ITOC project consortium from CMI, INRIM, NPL, OBSPARIS, PTB and LUH. The cooperation with the FACT ITN ensured that the school was well attended by students from universities as well as metrology institutes, and feedback about the school from both lecturers and students has been very positive. Its success has led to a second summer school covering similar topics being planned within the recently started 15SIB03 OC18 project.

Lectures on specific topics related to the work performed within our project have also been given at schools organised by others. For example a lecture on “Frequency standards with trapped ions” was given at a summer school on “Ion Traps for Tomorrow’s Applications”, held in Varenna, Italy in July 2013. Another on “Comparing optical clocks with 10^{-17} uncertainty” was given at a school on “Advanced atomic sources and extreme cooling of atoms and molecules: techniques and applications”, held in Les Houches, France in January 2016.

Further training on the areas covered by our project has been provided by consortium members in a range of seminars, colloquia and public lectures.

¹⁶ <http://quantsensors.org/innovation/activities/clocks/>

4.3 Dissemination activities

Beyond our input to metrology committees as detailed in section 4.1 above, the potential uptake of our research results by end users has primarily been promoted through a range of dissemination activities including our project website, publications in peer-reviewed journals, and presentations at conferences and workshops.

Thus far 17 papers have been published in the public domain and several more are in preparation. A list of publications is provided at the end of this report. 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.

Key metrology conferences at which project results have been disseminated are the European Frequency and Time Forum (EFTF), the IEEE International Frequency Control Symposium (IFCS) and the 8th Symposium on Frequency Standards and Metrology. Other conferences attracting a wider audience of scientists working in atomic physics and laser spectroscopy have also been attended, such as the International Conference on Laser Spectroscopy (ICOLS), the International Conference on Atomic Physics (ICAP), and the European Conference on Trapped Ions. We have made a particular effort to disseminate the results of our research to the geodesy community, with presentations having been given at conferences such as the International Association of Geodesy Scientific Assembly, the International Union of Geodesy and Geophysics General Assembly, and the European Geosciences Union General Assembly, as well as at an ISSI/HISPAC workshop on "High performance clocks, with special emphasis on geodesy and geophysics and applications to other bodies of the solar system".

A final international workshop on "Optical atomic clocks: quantum engineering and international timekeeping" was organised in cooperation with the EMRP-funded EXL01 QESOCAS "Quantum Engineered States for Optical Clocks and Atomic Sensors" project consortium. This was held in April 2016 in association with EFTF 2016 (University of York, UK), on the day after the main conference. Co-location with EFTF enabled us to attract a wide audience, with the workshop being attended by more than 70 participants. The majority came from European NMIs and academic research institutions, but there were also representatives from European SMEs (e.g. TOPTICA Photonics AG and TimeTech GmbH) and NMIs outside Europe, including NIST, NRC, NMIJ and KRISS. The workshop opened with two invited talks from leading experts in the field, including one focussing on a future redefinition of the second. This summarised achievements made with optical clocks to date and discussed the remaining challenges that still need to be addressed before a redefinition can occur. The invited talks were followed by presentations from members of the two project consortia. For the ITOC project, an overview of the work undertaken was given by the project coordinator, summarizing the main goals and the results achieved. A further talk described the campaign performed in June 2015 to compare optical clocks at INRIM, NPL, OBSPARIS and PTB via a broadband two-way satellite time and frequency transfer link. Other results from the project were presented in eight posters, providing a forum for detailed discussions between consortium members and stakeholders.

Formal collaborations with seven organisations were established during the project, contributing to the early dissemination of research results. LSM provided laboratory space and facilities for the proof-of-principle clock-based geodesy experiment. TimeTech GmbH, the Royal Observatory of Belgium and NICT all contributed in different ways to the optical clock comparison campaign performed in June 2015. The Politecnico di Torino collaborated in the geodetic measurements performed in Italy, whilst IMBIB and NIST participated via staff secondments of several months each to NPL.

4.4 Impact on fundamental physics

The international scientific community will benefit from validated clock comparisons as a basis for tests of fundamental physical theories. For example, theories aiming to unify the description of gravity with the standard model of particle physics predict violations of the Einstein Equivalence Principle, such as the time-variation of fundamental physical constants. Repeated measurements of the type performed in this project, i.e. comparisons between transition frequencies in high accuracy atomic clocks, can be used to search for present-day temporal variation in the fine structure constant and proton-to-electron mass ratio.

The demonstrated performance of the ground-based optical clocks and the lessons learned from the satellite-based clock comparison techniques explored within our project will also benefit fundamental science space missions such as the Atomic Clock Ensemble In Space (ACES) mission, which is due to be launched in 2018. The scientific objectives of the ACES mission include an alternative test of Einstein's theory of relativity, i.e. a high accuracy measurement of the gravitational redshift.

4.5 Impact on geodesy

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, and there are excellent prospects for improving the accuracy achieved in our initial experiment by orders of magnitude as the reliability and robustness of transportable optical clocks improves. High-resolution measurements of the gravity potential made using optical clocks at selected well-defined locations 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.

The measurement of sea level and ocean dynamics requires accuracy at the 1 cm level, through a combination of gravity and sea surface height measurements. Although the data obtained from satellite missions such as GOCE or GRACE, which provide global coverage, allow this to be achieved for spatial averages over length scales of about 100 km, at smaller length scales the geoid typically has 20 cm of variability, and more than 2 m in extreme cases. This leads to practical difficulties in making use of point measurements of sea level such as those from tide gauges. To account for these short length scales, a dedicated airborne gravity survey of the surrounding area, out to 100 – 200 km away from the tide gauge, must be carried out. Only a few regions are able to afford such surveys and even then achieving an accuracy of 1 cm is rather optimistic. A clock with a fractional uncertainty of 10^{-18} , when its frequency is compared with a similar reference clock, would provide a direct measurement of the gravity potential at the 1 cm level, allowing tide gauge levels to be determined in a much more straightforward and far more cost-effective way. Such measurements would have immediate practical impact in allowing the sea level dataset determined through satellite measurements to be connected to the much longer tide gauge records, and to link them to sea level precisely at the coast, where it is of most societal interest.

The potential applications of transportable optical clocks in geodesy are attracting increasing interest, as demonstrated by invitations to high-level conferences in the field and uptake of the topic introduced in our project by other large research centres (e.g. <http://www.geoq.uni-hannover.de/>).

4.6 Longer-term financial and social impact

Accurate time and frequency references underpin numerous technologies that we have come to take for granted in everyday life. For example, systems such as electric power grids, mobile telecommunication networks, the internet, electronic financial transactions and global navigation satellite systems (GNSS) all depend critically on time and frequency standards for their proper operation. The developments realised within this project will in the longer term enable time and frequency to be disseminated with unprecedented stability to users of international timescales and are thus expected to have widespread impact on innovation, science and daily life. Examples of some of the first users who can be expected to benefit from the availability of higher stability reference timescales include the European Space Agency (ESA) and the European VLBI Network (EVN), both of whom have major facilities (ESTEC, JIVE) that require accurate time and frequency signals.

5 Website address and contact details

The address of the public website for the project is www.optical-time.eu.

Enquiries about the project should be addressed in the first instance to the project coordinator, Dr Helen Margolis from NPL (helen.margolis@npl.co.uk).

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