Publishable Summary for 15SIB05 OFTEN
Optical frequency transfer - a European network

Overview

Optical clocks (OCs) outperform the best caesium (Cs)-based atomic clocks in terms of both accuracy and stability and are promising candidates for the redefinition of the SI unit of time, the second. Development and use of optical clocks, whether for metrology or applications in science, requires the capability to intercompare clocks without degrading their characteristics. Optical fibre has emerged as the only means to provide this capability over long distances. This project has developed techniques that improve the reliability and scalability of frequency transfer over optical fibre and has demonstrated continuous operation of long-distance fibre links with the measurement uncertainty required for optical clocks.

Need

Prior to the start of this project there was a need for comparing OCs on a regular basis at the corresponding level of uncertainty. As established satellite techniques developed for the comparison of primary Cs based clocks are inadequate for comparing OCs at the required level of uncertainty, it is generally agreed that frequency comparisons mediated by optical fibres provide the **only** means to compare OCs at a level of performance where the contribution of the frequency comparison becomes negligible compared to that of the clocks.

Objectives

The overall goal of the project was to compare optical clocks operated at European NMIs at the highest possible level of accuracy using frequency transfer over optical fibre links.

The project had the following objectives:

1. To connect two or more clocks belonging to NMIs in Europe with optical fibre links and enable multiple OC comparisons at a fractional instability level from 10^{-17} to 10^{-18}.
2. To assess and improve the accuracy and stability of remote optical frequency transfer by optical fibres, aiming for a fractional instability and uncertainty $<10^{-19}$ (over one day).
3. To develop techniques that improve the reliability and scalability of frequency transfer over optical fibre, striving for continuous measurements (more than one day duration) and simultaneous operation of branched long-distance links.
4. To operate long-distance optical fibre links (measurement uncertainty $<10^{-17}$ at one day) and to perform fast and accurate frequency comparisons (0.5-1 day duration, combined statistical Cs fountain clock uncertainty $2\text{-}3\times10^{-16}$) between Europe's Cs fountain clocks.
5. To develop applications of fibre-based frequency comparison and dissemination techniques for very long-baseline (VLBI >300 km) geodesy experiments and for ground-space-ground frequency comparisons, especially to assess the performance of the MicroWave Link (MWL) and/or the European Laser Timing Link (ELT) technology in the Atomic Clock Ensemble in Space (ACES), by simultaneously comparing clocks over both fibre and space links.
6. To facilitate the take up of the technology and measurement infrastructure developed within the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers) and end users (space, geodesy, telecommunications, etc.).

Progress beyond the state of the art

The enormous potential of optical carrier frequency transfer has been already demonstrated within the project SIB02 NEAT-FT. However, reliable operation of these links on an autonomous, day-to-day basis is needed. In addition, routine clock comparisons via optical fibres require further improvement of equipment and a deeper understanding of the noise processes limiting the stability of an optical fibre link as well as the development of real-time evaluation tools for multiple clock comparisons. Optical frequency transfer is ready for exploitation in other areas of sciences, such as high-resolution spectroscopy, geodesy and radio-astronomy. However, this requires adapting protocols and addressing specific challenges, such as the complexity of equipment.

This project went beyond the current state of the art and:

1. connected three NMIs in Europe by optical fibre links and performed comparisons of remote optical clocks;
2. improved the accuracy and stability of existing optical fibre links to the 10^{-19} level, implemented fault detection and management and investigated two-way techniques in terms of instability, reliability and sensitivity;
3. simplified the operation of cascaded optical fibre links, improved the robustness of links with software for monitoring remote equipment; and drafted a common data format for recording and sharing link data and a coordinated methodology to assess optical fibre link performance;
4. operated long-distance optical fibre links between NPL, OBSPARIS and PTB for accurate frequency comparisons between primary Cs fountain clocks; and developed a framework to enable fast, on-demand fountain comparisons with an uncertainty not limited by the link, i.e., below the combined uncertainty of the Cs fountain clock of $2\text{-}3 \times 10^{-16}$;
5. started a discussion with the ACES Working Group, to assess the performance of the MWL and/or ELT technology by simultaneously comparing clocks over both optical fibre and space links and with the *International Association of Geodesy* (IAG) concerning the benefit of improved frequency standards and traceability for geodesy e.g. VLBI observations;
6. developed applications of fibre-based frequency comparison and dissemination techniques for high-resolution spectroscopy and very long-baseline geodesy experiments, investigating the possibility of sharing the network architecture to simplify the equipment complexity.

Results

Connecting two or more optical clocks belonging to NMIs in Europe with optical fibre links and enable multiple OC comparisons at a fractional instability level from 10^{-17} to 10^{-18}.

Following the first international OC comparison using optical fibres in June 2015 [1], in total four additional optical clock comparison campaigns have been performed using the successfully established multi-NMI fibre link (NPL–OBSPARIS–PTB) leading to a test of special relativity [2], a comparison of primary Cs-fountain clocks [3], and the first direct measurement of the frequency ratio between a Hg lattice clock and an Yb^{+}-ion clock. In total up to 9 optical clocks, up to five primary Cs fountains and one Rb fountain have been compared simultaneously in multi-NMI comparison (NPL–OBSPARIS–PTB) limited only by the performance of the clocks involved. All clock comparisons performed so far have demonstrated the excellent frequency stability enabled by fibre-based optical frequency transfer, most of them reaching the low 10^{-17} level for the optical clocks within integration times less than one day. The demonstrated performance of optical clocks and fibre links have already opened the way for novel applications such as relativistic geodesy [4]. The campaigns revealed shortcomings in terms of performance, long-term operational capability, reliability of the participating fibre links, optical clocks, and frequency combs. While some of these issues have already been addressed early on, improving the technological readiness level of the participating equipment continues to be an important task for achieving the goal of hassle-free optical clock comparisons. This will be addressed in the follow-up EMPIR project TiFOON. The objective was achieved.

Assessing and improving the accuracy and stability of remote optical frequency transfer by optical fibres, aiming for a fractional instability and uncertainty $<10^{-19}$ (over one day).

For 2-3 days of integration, the mean frequency offset and the corresponding uncertainty over several fibre links (OBSPARIS-UoS (University of Strasbourg), OBSPARIS-LPL (Laboratoire de Physique des Lasers), LPL-NPL, PTB-UoS) have been determined demonstrating that frequency comparisons can be performed where the contribution of the fibre link to the overall uncertainty is at the low 10^{-19} level or below [5, 6, 7]. In order to feed several independent fibre link branches multi-user eavesdropping set ups [8], and the interplay between repeater laser stations (RLS) and fibre Brillouin amplifiers (FBA) have been investigated. In addition, the performance of two-way techniques was carefully analysed under fully realistic conditions, using two independent lasers and two independent acquisition set-ups. The effect of a time-base mismatch was elucidated. The results were published in Metrologia [9]. The objective was achieved.

Developing techniques that improve the reliability and scalability of frequency transfer over optical fibre, striving for continuous measurements (more than one day duration) and simultaneous operation of branched long-distance links.

As management of remote equipment along fibre links using the Global System for Mobile Communications (GSM) has in the past proven unsatisfactory, in-band monitoring with a communication channel in the C- or L-band was implemented in several links that now provides reliable remote control and monitoring. Links NPL-LPL, OBSPARIS-UoS, and INRIM-LENS (European Laboratory for Non-linear Spectroscopy) and INRIM-LSM (Laboratoire Souterrain de Modane) were upgraded with new bi-directional amplifiers from two different European manufacturers. In order to remotely assess the quality of fibre connections and to detect amplifier status, an optical frequency domain reflectometry (OFDR) technique has been implemented at NPL. Using an existing offset-locked transfer laser, interferometer and beat detection the OFDR has been successfully employed for fault detection and link diagnostics during recent hardware upgrades in France. This technique is very promising for improving the set-up time of a bi-directional fibre link. The objective was achieved.

Operating long-distance optical fibre links (measurement uncertainty <10^{-17} at one day) and performing fast and accurate frequency comparisons (0.5-1 day duration, combined statistical Cs fountain clock uncertainty 2-3×10^{-16}) between Europe's Cs fountain clocks.

A report summarising the network, rf-oscillators, optical and microwave transfer-oscillators, frequency standards and a working procedure for remote clock comparisons has been prepared and agreed. The procedure was largely implemented in the December 2018 clock comparison campaign. A three-way maser comparison between NPL, OBSPARIS and PTB demonstrated that the framework is suitable to be used for Cs fountain comparisons with an uncertainty meeting or exceeding the target, provided maser frequencies are known sufficiently well (about 1 part in 10^{14}) *a priori*. First pair-wise comparisons of Cs fountain clocks have been performed during the optical clock campaigns [2,3]. Based on the April and December 2018 clock comparison campaigns an additional comparison of Cs fountains between NPL, SYRTE and PTB was performed.

In the microwave domain PTB and AGH investigated the performance of optical time transfer links based on the ELSTAB technique connecting a facility of Deutsche Telekom in Bremen with Physikalisch-Technische Bundesanstalt in Braunschweig. A TDEV at the low ps-level at averaging times between 10^4 to 10^6 s has been achieved. The uncertainty of time transfer (including all kinds of delays) is of the order of 50 ps in a cascade of links [10, 11].

Time and radio frequency dissemination based on the ELSTAB technique was also realised between RISE in Borås and Onsala Space Observatory using the recently installed (2016) new Swedish Network, SUNET_C [12]. The network configuration allows flexible and reconfigurable time/frequency transfer to any client, and dispersion-compensated spools can be bypassed to increase the stability. After 1 day of integration, the frequency instability is at the 10^{-15} level and the time deviation remains below 100 ps.

Implementing several improvements, including a new ASIC and reduced thermal sensitivity, the ELSTAB system [13] has been improved significantly. The system now achieves an instability of 7×10^{-14} in a 0.5 Hz bandwidth at 1 s averaging time. Even in a case of poor air-conditioning in the hosting laboratory a long-term (1 day) stability at the target level of 10^{-16} has been obtained. In addition, a prototype of a hybrid laser systems comprising a cw laser with a PLL and the ELSTAB system has been tested for the first time allowing simultaneous transmission of a stable optical carrier and rf signals (10 MHz, 1pps) [14]. The objective was achieved.

Developing applications of fibre-based frequency comparison and dissemination techniques for long-baseline (>300 km) geodesy experiments and for ground-space-ground frequency comparisons, especially assessing the performance of the MicroWave Link (MWL) and/or the European Laser Timing Link (ELT) technology in the Atomic Clock Ensemble in Space (ACES), by simultaneously comparing clocks over both fibre and space links.

Stable optical reference frequencies have been provided to Leibniz University of Hanover (LUH) to measure the performance of their Mg lattice clock, to LENS to resolve weak physical effects in cold Yb spectroscopy [15, 16], to the VLBI Station in Medicina to synthesise a microwave signal substituting the rf signal of a local H-maser [17, 18], to the University Paris 13 (LPL) for broadband SI-traceable methanol spectroscopy in the midinfrared [19, 20]. This setup allowed identification of several spectral features in methanol and is now being used for spectroscopy of ammonia and trioxane as well. Traceability in the mid-IR domain has been achieved as well, using nonlinear optical conversion techniques to bridge the gap between 1542 nm and the 5.8 µm spectral range [21, 22].

There are now six VLBI sites in the world connected to primary frequency standards, five of which are in Europe: these include the Onsala telescope connected to RISE in Sweden, the Torun VLBI station connected to AOS in Poland [23], the Metsahovi telescope connected to VTT in Finland, and the telescopes in Medicina and Matera connected to INRIM in Italy. The link from INRIM to LENS has been further extended to southern Italy in order to reach the Galileo Control Center at Fucino and the VLBI stations at Matera [17].

In order to identify the benefits which VLBI observations obtain from improved frequency standards and traceability RISE and Chalmers have performed simulations based on Kalman filter solutions [24] to quantify uncertainties of the estimated parameters effecting the overall observation uncertainty of VLBI stations. Thus, the implementation of a common clock for all stations can improve the uncertainty only at the level of 15 – 30 % in the case of equal transmission delay to all observatories and an ideal time transmission.

Preliminary VLBI campaigns involving Italian antennas (Medicina Radio telescope, Noto-Sicily and the Space Geodesy Centre in Matera) where a common clock was shared between multiple telescopes took place in May 2019. Note that applications in radio-astronomy/ VLBI require in general frequency division of the optical signal down to the microwave/ rf- domain using frequency combs. Thus, in order to replace expensive commercial combs at the telescope sites a low-noise microwave generation setup based on a homemade frequency comb with repetition rate of 78.125 MHz and 7-stage repetition rate multiplier has been developed.

Several partners investigated the correlation between the noise of adjacent fibres and the achievable performance of frequency dissemination over DWDM networks with spans of telecom cables ranging between 90 km up to 2000 km in length [5, 6, 25, 26]. It appeared that in the general case, between 25 and 30 dB of phase noise can be rejected by implementing traditional noise-cancellation schemes over pairs of unidirectional fibres. On the Swedish SUNET-C testbed with up to 800 km of reconfigurable fibre routes [12], transmission of ultrastable optical frequency was substantially influenced by polarisation variations synchronous with the 50 Hz of the power grid. Techniques to compensate for such perturbations have been evaluated by Chalmers and RISE and form a base for further development [27, 28]. A test on the PSNC DWDM-network (up to 2000 km long) in Poland over three months showed a ModADEV of about $1x10^{-12}$ at 1 s integration time and a noise floor of about $1x10^{-16}$ after 10 000 s. The relative frequency offset averaged over 1 day was in the range of some 10^{-16} [29]. Issues related to broadband ASE noise and dispersion-compensated fibres (DCF) proved to be responsible for two orders of magnitude degradation in stability. The former has been fixed by optimising the bandwidth of receivers; the latter is no longer present in last-generation networks. A significant dependence on temperature in the housings where such spools are located was observed. Although it represents a strong limitation, extended analysis allowed to discover that indeed last-generation networks do not suffer from this issue [30]. The analysis was repeated with optical carrier transmission instead of RF transfer, showing consistency between results. A conservative estimation of the ultimate uncertainty of such links is at the 10^{-15} level and should always be verified on the specific implementation. The consortium concludes that DWDM frequency dissemination is a viable option for non-NMI users, once the proper attention is paid to the network design to check the absence of problematic components such as dispersion compensated spools, and aerial fibre paths.

Overall, the objectives of the project were achieved. The continuous postponement of the start date for the launch of ACES has prevented the implementation of any experiments comparing ACES MWL to fibre links. The fibre connections and the necessary equipment were provided for future use as planned.

Impact

The project outputs have been transferred to a wider community of stakeholders via the project web-site. Up to now 53 presentations and 16 posters were presented at international conferences such as the Workshop on Optical Clocks 2016, European Conference on Optical Communication (ECOC 2016, 2017), Precise Time and Time Interval Meeting (PTTI 2017, 2018), SPIE Photonic West, DPG Spring Meeting (DPG 2017), Annual Meeting of UTC Laboratories in Germany, ACES Workshop 2017, European Frequency and Time Forum (EFTF/ IFCS 2016, 2017, 2018, 2019), International Time & Sync Forum (ITFS 2017), International Symposium on Physics and Applications of Laser Dynamics (IS-PALD 2017), International Conference on Laser Spectroscopy (ICOLS 2017), the General Assembly and Scientific Symposium of the International Union of Radio Science (URSI-GASS 2017) and the Conference on Precision Electromagnetic Measurements (CPEM 2018).

Furthermore, the project has produced 17 high impact publications, 9 proceedings papers, one PhD Thesis (all open access, see below), and articles in the popular or trade/professional press and press releases of participating institutes (16). Members of the consortium have also given tutorials and lectures at external workshops and seminars (13) and a one-to-one training. In addition, the project has established an international advisory board to enable outputs from the project to be disseminated effectively and efficiently to all potential end-users.

Impact on industrial and other user communities

Project partners participated in the European Union-funded project CLONETS (Call H2020-INFRAINNOV-2016-1), which aims to prepare the transition from the present situation toward a permanent, pan-European, optical fibre-based network providing time and frequency comparisons and distribution at the highest performance levels for research infrastructures, as well as supporting a wide range of services for industry and society. CLONETS has brought together a diverse group of actors: National Metrology Institutes (NMIs), academic research groups, National Research and Education Network providers (NRENs), an internet exchange and small and medium-sized high-technology companies.

A permanent, pan-European, optical fibre-based network providing traceable time and frequency references – otherwise only available at NMIs – to additional regional end-users will pave the way for dissemination to industry and large-scale scientific projects. This project has laid the technical basis for the implementation of such a network and demonstrated the achievable performance.

The project has provided all means to support international space missions like ELT on board the International Space Station (ISS) once the space mission is on air. Moreover, together with the project OC18 the emerging field of chronometric levelling (by measuring the redshift of clocks in a gravitational field) has been promoted.

Impact on the metrology and scientific communities

The project has enabled fast on-demand clock comparisons and frequency dissemination by optical fibres between European NMIs. This has already boosted the development of OCs and facilitated the improvement of the uncertainty of secondary representations of the SI unit, the Second. As the stability of optical fibre links is orders of magnitudes higher than that of satellite links performing frequency comparisons of remote primary Cs fountain clocks via optical fibre links facilitated direct and real-time evaluation of primary Cs fountain clocks within a few days instead of weeks. Within the project good practice procedures for frequency transfer over optical fibres have been established by using a common data format for recording and sharing link data and by agreeing a coordinated methodology for assessing optical fibre link performance. This will ensure consistency in the evaluation of frequency comparisons of clocks across Europe.

By providing reference frequencies to remote laboratories outside of the current European time and frequency infrastructure these institutes have been able and will continue to perform direct SI traceable measurements.

Newly established research collaborations between PTB and AGH within the Polish Harmonia national funding, project CLONETS within the Horizon 2020 funding, as well as the follow-up EMPIR project TiFOON are directly related to the achievements within this project.

Impact on relevant standards

Improved values of the transition frequencies of optical clocks will have direct impact on the recommendations of standardisation bodies such as the EURAMET Technical Committee on Time and Frequency (TC-TF) and working groups within the Consultative Committee for Time and Frequency (CCTF) and Consultative Committee for Length (CCL), or recommendations of the Telecommunication Standardization Sector of the International Telecommunications Union (ITU-T) currently under revision (e.g. ITU-T G.8272.1/Y.1367.1). The consortium results have been presented at meetings of the EURAMET Technical Committee on Time and Frequency (TC-TF 2016,2017,2018,2019) and working groups within the Consultative Committee for Time and Frequency (CCTF), and at the Study Group 15 Question 13 on synchronisation of the ITU International Telecommunications Union.

Longer-term economic, social and environmental impacts

The research in this project leads to a continental infrastructure of metrological fibre links which would significantly strengthen Europe's position in the international metrological community, if a permanent European source of funding the network infrastructure outside the NMI is found.

Optical clocks linked by optical fibres will play an important role in earth observation by monitoring environmental changes with significantly higher spatial resolution than space-based missions like the GOCE or GRACE satellites. The combination of fibre links and ultraprecise optical clocks will in future allow the unification of height systems across the globe and eventually lead to a new definition of the geoid. Furthermore, the availability of optical reference frequencies with unprecedented stability and accuracy at dedicated remote locations will help European companies to maintain and extend their position in the growing worldwide market.

List of publications

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Project start date and duration:	June 2016, 36 months	
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Project website address: http://www.ptb.de/emrp/often_home.html		
Internal Funded Partners: 1 PTB, Germany 2 CMI, Czech Republic 3 INRIM, Italy 4 NPL, UK 5 OBSPARIS, France 6 RISE, Sweden 7 TUBITAK, Turkey	External Funded Partners: 8 AGH, Poland 9 Chalmers, Sweden 10 CNRS, France 11 PSNC, Poland	Unfunded Partners:
Linked Third Parties: 12 CNRS, France (linked to OBSPARIS)		
RMG: -		

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