FINAL PUBLISHABLE REPORT

Grant Agreement number	15SIB05
Project short name	OFTEN
Project full title	Optical frequency transfer - a European network

Project start date and duration:	June 2016, 36 months	
Coordinator: Harald Schnatz, PTB	Tel: +49 531 592 4300	E-mail: Harald.Schnatz@ptb.de
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: -		

TABLE OF CONTENTS

1 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.

2 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.

3 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.).

4 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 initial 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). This work was supported by CMI preparing a literature overview of current methods of gravity field modelling in the context of optical clock comparisons.

In the **first campaign**, clocks at OBSPARIS and NPL have been compared **in June 2016**. Data from both campaigns has been used to perform a test of special relativity [2] and a comparison of primary Cs-fountain clocks [3]. Further to this, the formerly distinct links between PTB and OBSPARIS and that between OBSPARIS and NPL have been successfully transformed into a multi-NMI fibre link (NPL–OBSPARIS–PTB), which now allows clock comparisons limited only by the performance of the clocks involved.

The **second campaign in June 2017** has been the first multi-NMI comparison (NPL–OBSPARIS–PTB) including multiple OCs leading to the first direct measurement of the frequency ratio between a Hg lattice clock and an Yb^+-ion clock. In total up 9 optical clocks, and up to five primary Cs fountains and one Rb fountain have been compared simultaneously. In addition, several optical frequency combs have been operated to connect the clocks to the fibre links.

During the **third campaign in April 2018** five optical clocks at all three institutes participated: Sr(NPL), 2 Sr(OBSPARIS), Sr(PTB), and Yb^+(PTB). Here, for the first time the frequency ratio Sr(NPL)/Sr(PTB) could be measured over about 32 hours of overlapping operation. The instability of the frequency ratio averaged down below the combined estimated systematic uncertainty of the two clocks. The frequency offset between the two clocks has been comparable to the combined estimated systematic uncertainty.

The **fourth campaign** took place **in December 2018**. During this multi-clock comparison again six OCs participated: Sr(NPL), Yb+(NPL), 2 Sr(OBSPARIS), Hg(OBSPARIS), and Yb+(PTB). Among others, the frequency ratio Yb+(PTB)/Yb+(NPL) could be measured for the first time over an extended time period leading to a statistical uncertainty in the low 10^{-17} range.

During all optical clock comparison campaigns, data for the operational Cesium fountains (CsF) at the three NMIs has been recorded as well.

All clock comparisons 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 performed by NPL, OBSPARIS, CNRS, and PTB 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 continued 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.

Objective 1 was overachieved by carrying out more frequency comparisons than originally planned.

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).

The existing fibre links OBSPARIS-UoStrasbourg (University of Strasbourg) and the LPL (Laboratoire de Physique des Lasers, Paris) -NPL link were investigated with respect to the detection and processing of corrupted data and their impact on the accuracy of the frequency transfer. For 2-3 days of integration, a mean frequency offset of -1.8×10^{-20} with a statistical uncertainty of 8×10^{-20} was obtained for the OBSPARIS-UoStrasbourg link. For the SYRTE (Systèmes de Référence Temps-Espace, Paris) -LPL link, the accuracy is

1 C. Lisdat *et al.; A clock network for geodesy and fundamental science*, Nature Com. 7, 12443 (2016)
2 P. Delva *et al.; Test of Special Relativity Using a Fiber Network of Optical Clocks*, Phys. Rev. Lett. 118, 221102 (2017)
3 J Guéna *et al.; First international comparison of fountain primary frequency standards via a long distance optical fiber link,* Metrologia 54 348, (2017)
4 T. Mehlstäubler *et al.*; *Atomic clocks for geodesy*, Rep. Prog. Phys. 81 (2018) 064401

conservatively set to 4×10^{-20}, dominated here also by statistical uncertainty [5]. More recently fundamental limits of fibre links were investigated using the OBSPARIS-LPL link in a hybrid architecture, combining active and passive cancellation techniques [6].

Fibre links combining fibre Brillouin amplifiers (FBA) and repeater laser stations (RLS) have been thoroughly investigated and a new design of FBA modules allowing for easier compensation of polarisation changes has been developed. On the PTB-UoStrasbourg-PTB link, the locking capability of the software steering the FBAs was enhanced, and factors restricting the time of continuous operation have been elucidated [7].

Multi-user eavesdropping set ups were investigated, using an offset phase lock laser to feed several fibre link's branches [8]. Multi-branch repeater laser stations have been developed for the REFIMEVE+ (Réseau Fibré Métrologique à Vocation Européenne) project and included into the joint fibre link. The stability and accuracy of this new device were analysed. Frequency instability is at the level of 5×10^{-20} at one day integration time in the worst case.

Performance of two-way techniques were 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].

Reaching significantly below 10^{-19} level of relative frequency uncertainty objective 2 was overachieved.

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.

Management of some bi-directional amplifiers with Global System for Mobile Communications (GSM) has in the past proven unsatisfactory. Links NPL-LPL, OBSPARIS-UoStrasbourg, and INRIM-LENS (European Laboratory for Non-linear Spectroscopy, Florence) and INRIM-Modane (Laboratoire Souterrain de Modane) were upgraded with new bi-directional amplifiers from two different European manufacturers. In-band monitoring with a communication channel in the C- or L-band was implemented in all these links and provided reliable remote control and monitoring.

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.

With the continuously operated fibre links branching at OBSPARIS to NPL and to PTB and that branching at INRIM to Modane or Florence, objective 3 has been achieved as planned.

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$\times10^{-16}$) between Europe's Cs fountain clocks.

A complete ELSTAB (Electronically stabilised) system [10] implementing several improvements, including a new application-specific integrated circuit (ASIC), has been assembled and tested. An instability of 0.7×10^{-13} at 1 s averaging time and in a 0.5 Hz bandwidth has been demonstrated. The thermal sensitivity of the ELSTAB units has been reduced by a factor of five, which allows to obtain a long-term (1 day) stability at the target level of 10^{-16} even in a case of poor air-conditioning in the hosting laboratory.

In addition, PTB and AGH have developed a prototype of a hybrid laser systems comprising a cw laser with a PLL and the ELSTAB system that allows for simultaneous transmission of a stable optical carrier and rf signals (10 MHz, 1pps) [11].

5 W.-K. Lee, *et al.; Hybrid fiber links for accurate optical frequency comparison*, *Appl. Phys.~B* **123**, 161 (2017)

6 Xu, D. *et al.; Studying the fundamental limit of optical fiber links to the 1e-21 level*. Opt. Express, OE 26, 9515–9527 (2018).

7 S. Koke, C. Grebing, A. Kuhl, G. Grosche, „*Validating frequency transfer via a stabilised fibre link for optical clock comparisons*", EFTF 2016

8 A. Bercy, O. Lopez, P.-E. Pottie and A. Amy-Klein; *Ultrastable optical frequency dissemination on a multi-access fibre network*, Appl. Phys.**B 122**, 189 (2016)

9 A. Tampellini, *et al.*; *Effect of a timebase mismatch in two-way optical frequency transfe*r, Metrologia **54**, 805 (2017)

10 P. Krehlik, *et al., ELSTAB—Fiber-Optic Time and Frequency Distribution Technology: A General Characterization and Fundamental Limits,* IEEE TUFFC 63, 993-1004, July 2016.

11 Krehlik, P., Schnatz, H., and Sliwczynski, L.; *A hybrid solution for simultaneous transfer of ultrastable optical frequency, RF frequency and UTC time-tags over optical fiber*, Vol 64, 1884-1890,(2017)

A draft paper 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 partially implemented in the third clock comparison campaign, e.g. hardware-based synchronisation derived from own UTC(k) or GNSS signals has been shown to be necessary to guarantee both the stability and accuracy required for clock comparisons over optical fibre links.

First pair-wise comparisons of Cs fountain clocks have been performed during the optical clock campaigns [2, 3]. Data recorded during the optical clock comparison campaigns in June 2017 and April 2018 should also allow to compare fountains between PTB, SYRTE and NPL.

Data from the April and December 2018 campaigns has been used to perform a three-way maser comparison between NPL, OBSPARIS and PTB. The results demonstrate 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*. Due to the large amount of data that needs to be validated for a systematic evaluation, a publication is still pending.

With the first three-way maser comparison between NPL, OBSPARIS and PTB and pairwise fountain comparisons objective 4 has been achieved as planned.

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.

A stable optical reference frequency was provided to the University of Hanover. PTB used its Sr lattice clock in combination with the fibre link to LUH to measure the performance of the Mg lattice clock of LUH. A publication is planned.

An optical reference at 1.5 µm was provided as a reference for a frequency comb at the University Paris 13 (LPL) and for broadband SI-traceable methanol spectroscopy in the midinfrared [12,13]. Using a frequency comb, a CO_2 laser and a Quantum Cascade Laser (QCL) have been stabilised to the remote reference reaching a fractional stability of around $2x10^{-15}$ from 1 to 100 s and a linewidth of 0.2 Hz. In addition, tunability exceeding 400 MHz was achieved. 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 1542 nm with the 5.8 µm spectral range. The first complete characterisation of the cw difference-frequency generation process in an OP-GaP crystal has been performed leading to a significantly increased idler power of ~65 µW at 5.85 µm [14, 15].

Cold Yb spectroscopy has been performed at LENS using a long-term stable optical reference provided by INRIM via optical fibre [16]. This enabled fast and repeatable atoms interrogation, in turns allowing to resolve weak physical effects [17]. The link 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 [18].

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

[12] Tran *et al., Frequency comb-assisted QCL stabilization for testing fundamental physics with molecules,* 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)

[13] R. Santagata, *et al., High-precision methanol spectroscopy with a widely tunable SI-traceable frequency-comb-based mid-infrared QCL*, Optica 6, 411-423 (2019)

[14] G. Insero *et al.; Difference frequency generation in the mid-infrared with orientation-patterned gallium phosphide crystals*, Opt. Lett. 41, 5114-5117 (2016)

[15] G. Insero, et al.; *Measuring molecular frequencies in the 1-10 µm range at 11-digits accuracy*, Scientific Reports 7, 12780 (2017)

[16] C. Clivati et al.; *Measuring absolute frequencies beyond the GPS limit via long-haul optical frequency dissemination,* Opt. Expr. 24, 11865 (2016)

[17] L. Livi et al.; *Synthetic Dimensions and Spin-Orbit Coupling with an Optical Clock Transition,* Phys. Rev. Lett. 117, 220401 (2016)

[18] D. Calonico, *et al.;* "The Italian optical link for time and frequency," 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), Besancon, 2017, pp. 156-159.

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 [19, 20].

Time and RF-Frequency dissemination based on the ELSTAB technique was realised between RISE in Borås and Onsala Space Observatory using the recently installed (2016) new Swedish network, SUNET_C [21]. This network is laid across the country on high-voltage power lines and is connected to NorduNet (the network of nordic countries) and to GÉANT (pan-European data network). 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 1E-15 level and the time deviation remains below 100 ps.

A rf-signal for substituting a local H-maser was delivered via fibre to the VLBI Station in Medicina [18,22]. Here the optical reference was provided to the remote end where a frequency comb then was used to synthesise a microwave signal (a harmonic of the combs' repetition rate). From this, a 10 MHz, 5 MHz and 1 PPS signals were generated and used in dedicated VLBI observations campaigns. The setup is now autonomously maintained by the radio telescope staff and is being used on demand for dedicated observations.

Preliminary VLBI campaigns involving Italian antennas (Medicina Radio telescope, Noto-Sicily and the Space Geodesy Centre in Matera) using local clocks have been performed in preparation of common-clock experiments involving Medicina and Matera telescopes. The link extension from Medicina Radio telescope to Matera has been established and fully characterised and the first common-clock VLBI experiments took place in May 2019. Data are now being analysed.

RISE and Chalmers have performed simulations based on Kalman filter solutions [23] to quantify uncertainties of the estimated parameters effecting the overall observation uncertainty of VLBI stations, with the ultimate goal of identifying the benefits which VLBI observations obtain from improved frequency standards and traceability. For this, a regular 24-hour experimental observation-run was used as template for the simulations. In general, the variations of the Zenith Wet Delay (ZWD) will always limit the resolution of VLBI observations. 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.

With such links, there are now six VLBI sites in the world connected to primary frequency standards, five of which are in Europe: these include the telescopes in Medicina and Matera connected to INRIM in Italy, the Onsala telescope connected to RISE in Sweden, the Torun VLBI station connected to Borowiec Astrogeodynamic Observatory (AOS) in Poland [24], and the Metsahovi telescope connected to VTT in Finland.

In order to replace commercial combs at the telescope sites TUBITAK developed a low-noise microwave generation setup. Various configurations have been tested (a soliton, a soliton-similariton and a stretched-pulse Er-fibre laser), and the soliton-similariton approach was then selected as more stable and robust. The microwave generation stage, based on a laser with repetition rate of 78.125 MHz and 7-stage repetition rate multipliers using single-mode fibre couplers, has been built by TUBITAK.

The achievable performance of frequency dissemination over Dense Wavelength Division Multiplexing (DWDM) networks has been investigated by several partners. Three DWDM testbeds were used to study the correlation between the noise of adjacent fibres: spans of telecom cables with length ranging between 90 km and 145 km, which will be part of a long-haul connection between INRIM and OBSPARIS; several fibre spans, with length ranging from few tens to up to 2000 km on the Polish network maintained by PSNC; and up to 800 km reconfigurable fibre spans of the last-generation SUNET-C network in Sweden. Most DWDM networks are equipped with reconfigurable add/drop multiplexers and hybrid EDFA/Raman amplifiers. The Swedish network is partly established along aerial high-voltage power lines.

[19] Ł. Śliwczyński *et al*., "Fiber optic time transfer between PTB and Deutsche Telekom using multi-link redundant topology," *2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, Besancon, 2017, pp. 681-682.

[20] Ł. Śliwczyński *et al;* "Calibrated Optical Time Transfer of UTC(k) for Supervision of Telecom Networks", Metrologia **56** (2019) 015006

[21] S.C. Ebenhag, "Evaluation of Fiber Optic Time and Frequency Distribution System in a Coherent Communication Network," proc. of the IFCS-EFTF2019, Orlando, Florida

[22] Clivati *et al., A VLBI experiment using a remote atomic clock via a coherent fibre link,* Scientific Reports 7, 40992 (2017)

[23] from Soja *et al.;* "Tropospheric delay determination by Kalman filtering VLBI data", Earth, Planets and Space (2015) 67:144

[24] P. Krehlik et al., "Fibre-optic delivery of time and frequency to VLBI station," Astron. Astrophys. 603, A48 (2017).

- INRIM measured the reciprocity of noise in spans of fibres with length ranging between 90 and 145 km, in presence of non-symmetrical amplifiers housings on the two adjacent fibres [25], and derived a model to quantify the noise reciprocity [26]; OP with LPL investigated reciprocity in a 86 km regional fibre [6]. From a comparison of the results, and also taking in consideration previous results achieved by OP-LPL in a 100 km urban network [8], it appears 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 SUNET-C testbed with up to 800 km of reconfigurable fibre routes [21], transmission of ultrastable optical frequency was substantially influenced by polarisation variations in phase with the 50 Hz of the power grid. Techniques to compensate for this, perturbations have been evaluated by Chalmers and RISE and form a base for further development [27,28].
- AGH and PSNC performed measurements on the long-distance (up to 2000 km long) PSNC DWDM-network in Poland over three months. The instability expressed as ModADEV reached 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 range of some 10^{-16} [29]. Issues related to broadband ASE noise and dispersion-compensated fibres 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 are no longer present in last-generation networks [30]. The analysis was repeated with optical carrier transmission instead of radio frequency transfer, showing consistence between achievable results.

To support these activities a transportable ultra-stable, cavity-stabilised narrow-linewidth laser at 1.5 µm has been developed by PTB. The system was completed, tested and characterised successfully.

On the long term, frequency instability in the 10^{-16} range has been achieved [6,29,30]. 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 activities performed in this task show that DWDM frequency dissemination is a viable option for non-NMI users, once the proper attention is paid to the network designed to check the absence of problematic components such as dispersion compensated spools, and aerial paths.

Due to the delays of the ACES mission a direct comparison between ground and space links could not be performed. However, this issue was not under control of the consortium. Dissemination of ultra-stable reference signal to end users demonstrated the superior performance of fiber-optic- based techniques in contrast to satellite- techniques. As the fiber-based infrastructure supporting the space missions is in place we regard objective 5 as achieved.

5 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

[25] Unpublished results

[26] C. Clivati *et al.; Optical frequency transfer over submarine fiber links*, Optica, Vol. 5, Issue 8, pp. 893-901 (2018)

[27] S-C. Ebenhag, et al, "*Measurement and Analysis of Polarization Variations in an Optical Coherent Fiber Communication Network Utilized for Time and Frequency Distribution*," Proceedings of the 49th Annual Precise Time and Time Interval Systems and Applications Meeting, Reston, Virginia, January 2018, pp. 233-236.

[28] P. O. Hedekvist, et al "*Analysis and compensation of polarization in an optical frequency transfer through a fiber communication network*", 32nd European Frequency and Time Forum (EFTF), Torino, Italy April 2018 pp. 253-256.

[29] K. Turza, et al.; *Time and frequency transfer in modern DWDM telecommunication networks*, 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC)

[30] K. Turza et al., *Long haul time and frequency distribution in different DWDM systems,* IEEE UFFC, vol. 65, issue 7, July 2018.

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.

6 List of publications

1. *A clock network for geodesy and fundamental science,*
C. Lisdat, G. Grosche, N. Quintin, C. Shi, S.M.F. Raupach, C. Grebing, D. Nicolodi, F. Stefani, A. Al-Masoudi, S. Dörscher, S. Häfner, J.-L. Robyr, N. Chiodo, S. Bilicki, E. Bookjans, A. Koczwara, S. Koke, A. Kuhl, F. Wiotte, F. Meynadier, E. Camisard, M. Abgrall, M. Lours, T. Legero, H. Schnatz, U. Sterr, H. Denker, C. Chardonnet, Y. Le Coq, G. Santarelli, A. Amy-Klein, R. Le Targat, J. Lodewyck, O. Lopez, P.-E. Pottie;
Nature Communications **7**, 12443 (2016), https://doi.org/10.1038/ncomms12443

2. *Test of special relativity using a fiber network of optical clocks,*
P. Delva, J. Lodewyck, S. Bilicki, E. Bookjans, G. Vallet, R. Le Targat, P.-E. Pottie, C. Guerlin, F. Meynadier, C. Le Poncin-Lafitte, O. Lopez, A. Amy-Klein, W.-K. Lee, N. Quintin, C. Lisdat, A. Al-Masoudi, S. Dörscher, C. Grebing, G. Grosche, A. Kuhl, S. Raupach, U. Sterr, I. R. Hill, R. Hobson, W. Bowden, J. Kronjäger, G. Marra, A. Rolland, F. N. Baynes, H. S. Margolis, P. Gill;
Phys. Rev. Lett. 118, 221102 (2017), https://arxiv.org/abs/1703.04426

3. *First international comparison of fountain primary frequency standards via a long distance optical fiber link,*
J. Guéna, S. Weyers, M. Abgrall, C. Grebing, V. Gerginov, P. Rosenbusch, S. Bize, B. Lipphardt, H. Denker, N. Quintin, S. M. F. Raupach, D. Nicolodi, F. Stefani, N. Chiodo, S. Koke, A. Kuhl, F. Wiotte, F. Meynadier, E. Camisard, C. Chardonnet, Y. Le Coq, M. Lours, G. Santarelli, A. Amy-Klein, R. Le Targat, O. Lopez, P. E. Pottie and G. Grosche;
Metrologia **54,** 348–354 (2017), https://doi.org/10.1088/1681-7575/aa65fe

4. *Ultrastable optical frequency dissemination on a multi-access fibre network*
Anthony Bercy, Olivier Lopez, Paul-Eric Pottie and Anne Amy-Klein;
Appl. Phys. **B122**, 189 (2016), https://doi.org/10.1007/s00340-016-6463-3

5. *Hybrid fiber links for accurate optical frequency comparison,*
Won-Kyu Lee, Fabio Stefani, Anthony Bercy, Olivier Lopez, Anne Amy-Klein, and Paul-Eric Pottie;
Appl. Phys. **B123,** 161 (2017), https://doi.org/10.1007/s00340-017-6736-5

6. *Effect of a timebase mismatch in two-way optical frequency transfer,*
A. Tampellini, C. Clivati, A. Mura, F. Levi, D. Calonico*;*
Metrologia **54**, 805 (2017), https://doi.org/10.1088/1681-7575/aa8a41

7. *Measuring molecular frequencies in the 1-10 µm range at 11-digits accuracy,*
G. Insero, G. Insero, S. Borri, D. Calonico, P. Cancio Pastor, C. Clivati, D. D'Ambrosio, P. De Natale, M. Inguscio, F. Levi, and G. Santambrogio;
Scientific Reports **7**, 12780 (2017), https://doi.org/10.1038/s41598-017-12891-6

8. *Synthetic Dimensions and Spin-Orbit Coupling with an Optical Clock Transition,*
L. F. Livi, G. Cappellini, M. Diem, L. Franchi, C. Clivati, M. Frittelli, F. Levi, D. Calonico, J. Catani, M. Inguscio, L. Fallani;
Phys. Rev. Lett. **117**, 220401 (2016), https://arxiv.org/abs/1609.04800

9. *A hybrid solution for simultaneous transfer of ultrastable optical frequency, RF frequency and UTC time-tags over optical fiber;*
P. Krehlik, H. Schnatz and Ł. Śliwczyński,
IEEE Trans. Ultrason., Ferroelectr., Freq. Control, Vol. 64, 1884 - 1890, (2017), https://doi.org/10.1109/tuffc.2017.2759001

10. *A VLBI experiment using a remote atomic clock via a coherent fibre link*,
C. Clivati, R. Ambrosini, T. Artz, A. Bertarini, C. Bortolotti, M. Frittelli, F. Levi, A. Mura, G. Maccaferri, M. Nanni, M. Negusini, F. Perini, M. Roma, M. Stagni, M. Zucco, D. Calonico;
Scientific Reports **7**, 40992 (2017), http://dx.doi.org/10.1038/srep40992

11. *Frequency comb-assisted QCL stabilization for high resolution molecular spectroscopy*,
D.B.A. Tran, R. Santagata, O. Lopez, B. Argence, S. Tokunaga, M. Abgrall, Y. Le Coq, R. Le Targat,

D. Nicolodi, W.-K. Lee, D. Xu, P.-E. Pottie, B. Darquié, A. Amy-Klein;
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium,
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf

12. *The Italian Optical Link for Time and Frequency*,
D.Calonico, C. Clivati, A. Mura, A. Tampellini and F. Levi;
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium,
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf

13. *Time and frequency transfer in modern DWDM telecommunication networks*
K. Turza, A. Binczewski, W. Bogacki, P. Krehlik, Ł. Śliwczyński,
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium,
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf

14. *Fiber optic time transfer between PTB and Deutsche Telekom using multi-link redundant topology, Ł. Śliwczyński,* P. Krehlik, J. Kołodziej, H. Imlau, H. Ender, H. Schnatz, D. Piester, A. Bauch*,*
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, Besancon, 2017, pp. 681-682,*
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf

15. *Progress on the REFIMEVE+ project for optical frequency standard dissemination*
Camisard, E., Pottie, P.E., Lopez, O., Amy-Klein, A., Chardonnet, C., Wiotte, F, Quintin, N., Cantin, E. and Santarelli, G.
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC) (2017)
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf and http://dx.doi.org/10.1109/FCS.2017.8088897

16. *Hybrid optical link for ultra-stable frequency comparison*
Lopez, O., Lee, W.K., Stefani, F. Pottie, P.E., Xu, D. and Amy-Klein, A.
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC) (2017)
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf

17. *CLONETS – Clock network services strategy and innovation for clock services over optical-fibre networks*
Schnatz, H., Grosche, G., Turza, K., Bogacki, W., Binczewski, A., Urbaniak, R., Nogaś, P., Stefl, J., Snajder, M., John, F., Tuckey, P., Tavares, R., Pottie, P.E., Whibberley, P., Kronjäger, J., English, E.L., Lautier-Gaud, J., Desruelle, B., Camargo, F., Lessing, M., Holzwarth, R., Rerucha, S. (ISI, Brno, CZ), Číp, O. Levi, F., Clivati, C., Calonico, D., Campanella, M., Vojtech, J., Velc, R., Smotlacha, V., Radil, J., Dostal, J., Śliwczyński, L., Krehlik, P., Camisard, E., Quintin, N., Diaz, J., Garcia, T., Ros, E., Galardini, A., Seeds, A., Yang, Z. and Amy-Klein, A.
2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC) (2017)
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2017.pdf

18. *Long haul time and frequency distribution in different DWDM systems,*
K. Turza, P. Krehlik, Ł. Śliwczyński,
IEEE Trans. Ultrason., Ferroelectr., Freq. Control, vol. 65, 1287-1293, (2018),
https://doi.org/10.1109/TUFFC.2018.2827178

19. *Optical frequency transfer over submarine fiber links*,
C. Clivati, A. Tampellini, A. Mura, F. Levi, G. Marra, P. Galea, A. Xuereb and D. Calonico,
Optica 5, 893-901 (2018), https://doi.org/10.1364/OPTICA.5.000893

20. *Atomic clocks for geodesy*,
T. Mehlstäubler, G. Grosche, C. Lisdat, P. Schmidt and H. Denker;
Rep. Prog. Phys. 81 (2018) 064401, https://arxiv.org/abs/1803.01585

21. *Studying the fundamental limit of optical fiber links to the 1e-21 level,*
D. Xu, W.-K. Lee, F. Stefani, O. Lopez, A. Amy-Klein, and P.-E. Pottie,
Opt. Express, OE 26, 9515–9527 (2018), https://doi.org/10.1364/OE.26.009515

22. *High-precision methanol spectroscopy with a widely tunable SI-traceable frequency-comb-based mid-infrared QCL*,
R. Santagata, D. B. A. Tran, B. Argence, O. Lopez, S. K. Tokunaga, F. Wiotte, H. Mouhamad, A. Goncharov, M. Abgrall, Y. Le Coq, H. Alvarez-Martinez, R. Le Targat, W. K. Lee, D. Xu, P.-E. Pottie, B. Darquié, and A. Amy-Klein*,*
Optica 6, 411-423 (2019), https://doi.org/10.1364/OPTICA.6.000411

23. *Analysis and compensation of polarization in an optical frequency transfer through a fiber communication network,*
P. O. Hedekvist, L. Weddig and S.-C. Ebenhag;
32nd European Frequency and Time Forum (EFTF), Torino, Italy April 2018 pp. 253-256,
https://www.eftf.org/fileadmin/conferences/eftf/documents/Proceedings/proceedingsEFTF2018.pdf

24. *Two-Branch Fiber Link for International Clock Networks,*
Xu, D., Cantin, E., Frank, F.,Quintin, N., Meynadier, F., Tuckey, P., Amy-Klein, A., Lopez, O., and Pottie, P.E.
IEEE Transactions on Instrumentation and Measurement 68 (2019), 2195-2200
https://doi.org/10.1109/TIM.2018.2886865

25. *Coherent fibre-optic link: applications in Time and Frequency Metrology, Geodesy, Radioastronomy and Seismology,*
A. Tampellini, PhD Thesis; Doctoral Program in Metrology (31.th cycle), Publisher Politecnico di Torino,
https://iris.polito.it/retrieve/handle/11583/2742522/258655/Thesis_Tampellini.pdf

26. *Spectral purity transfer with 5E-17 instability at 1 s using a multibranch Er:fiber frequency comb*,
P. Barbieri, Metrologia 56 (2019) 045008, https://doi.org/10.1088/1681-7575/ab2b0f

7 Contact details

Harald Schnatz
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany
Phone: ++49 531 592-4300
E-Mail: Harald.Schnatz@PTB.de
Homepage: www.ptb.de

Sebastian Koke
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany
Phone: ++49 531 592-43442
E-Mail: Sebastian.Koke@PTB.de
Homepage: www.ptb.de

Paul Eric Pottie
LNE-SYRTE - Observatoire de Paris
61, avenue de l'Observatoire
75014 Paris, France
phone: +33 (0)1 40 51 22 22
E-Mail: Paul-Eric.Pottie@obspm.fr
Homepage:

Cecilia Clivati
Istituto Nazionale di Ricerca Metrologica
Strada delle Cacce 91
IT-10135 Torino, Italy
Phone:
E-Mail: c.clivati@inrim.it
Homepage:www.inrim.it

Jochen Kronjäger
National Physical Laboratory
Hampton Road,
TW11 0LW,
Teddington, UK
Phone:
E-Mail: Jochen.Kronjaeger@npl.co.uk

Jan Gersl
Cesky Metrologicky Institut Brno
Okružní 31,
CZ-638 00 Brno, Czech Republic
Phone: +420 266 773 426
E-Mail:kuna@ufe.cz
Homepage: www.ure.cas.cz

Per Olof Hedekvist
SP Technical Research Institute of Sweden
Box 857
SE -501 15 Borås, Sweden
Phone: +46 10-516 50 00
E-Mail: per.olof.hedekvist@sp.se
www.sp.se/en/index/research/ICT/Sidor/default.aspx

Magnus Karlsson
Chalmers tekniska hoegskola AB

SE-412 96 Göteborg, Sweden
Phone: +46-73-079 4269
E-Mail: Magnus.karlsson@chalmers.se
Homepage:

Krzysztof Turza
Poznan Supercomputing and Networking Center (PSNC)
Noskowskiego 12/14
PL-61-704 Poznan, Poland
Phone: (4861) 8582023
E-Mail: kturza@man.poznan.pl

Przemysław Krelik
Akademia Gorniczo-Hutnicza im. Stanislawa Staszica w Krakowie
Al. Mickiewicza 30,
PL 30-059 Krakow, Poland
Phone: 12-6172740
E-Mail: krehlik@agh.edu.pl

Anne AMY-KLEIN
Laboratoire de Physique des Lasers
Université Paris 13, Sorbonne Paris Cité - CNRS
99 av J B Clément
FR-93430 Villetaneuse, France
Phone: 33 (0)1 49 40 33 79
E-Mail: amy@univ-paris13.fr
Homepage: www-lpl.univ-paris13.fr

Cagri Senel
Turkiye Bilimsel ve Teknolojik Arastirma Kurumu
Ataturk Bulvari 221,
TR-06100 Ankara, Turkey
Phone:
E-Mail: cagri.senel@tubitak.gov.tr
Homepage:

Nadine Weber (administrative contact)
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany
Phone: ++49 531 592-4012
Fax: ++49 531 592-4015
E-Mail: Nadine.Weber@PTB.de
Homepage: www.ptb.de